5G Broadband 2018: Architecture and Market Outlook

Abstract:

This report provides an end-to-end view of 5G broadband architecture, including detailed cost estimates for network and handset implementation. The impact of Massive MIMO, CRAN implementation, and Mobile Edge Computing are considered. Many questions on RF implementation have now been answered in RRH and handset design, and detailed power consumption and cost analysis shows the likely choices of OEMs. A 7-year forecast includes base station and RRH deployment (macro and small cell), as well as CPEs, mobile handsets/smartphones, tablets, and IoT devices.

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MOBILE EXPERTS

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1 EXECUTIVE SUMMARY

For the past twenty years, the mobile industry has deployed new generations of infrastructure to support new services. We bought 2G phones to have truly wireless phone capability. We used 3G for email. We use 4G phones for the Internet, but as we evolve to Gigabit LTE, we find that companies like Apple don't have any use for higher speeds. In the recent iPhone X, Apple chose not to implement 4x4 MIMO because higher speed really wasn't useful to them. What is 5G for?

Our view is that the main "unmet need" in the telecom market is the ability to deliver high-definition video at low cost. People would like to stream HD video content to their handsets, but on LTE it's too expensive. Fixed broadband users typically consume about 180-200 GB per month, while even the most aggressive mobile networks support about 30GB per month per user.

We believe that 5G is primarily about reducing the cost of video traffic. Yes, there are interesting IoT scenarios but all of those represent small market opportunities that might grow into bigger markets over the long term. Only the video/entertainment market has the potential to move the needle on the trillion-dollar mobile industry.

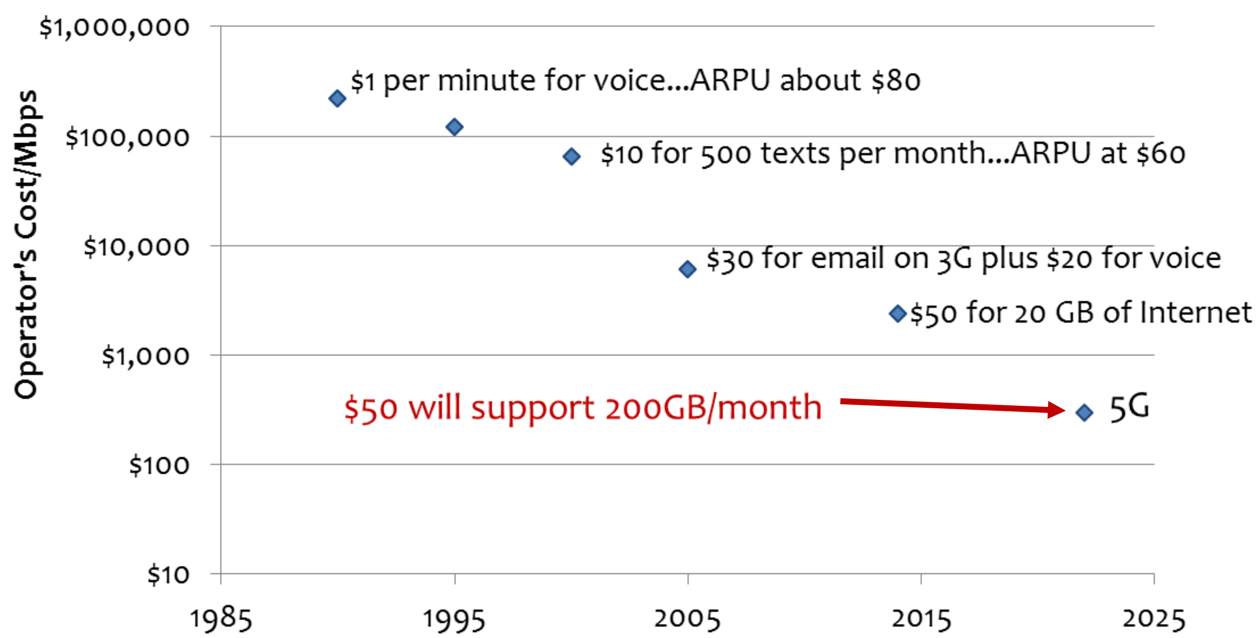

Figure 1 5G Strategic view

Source: Mobile Experts

The most important strategic conclusion here is that mobile operators don't need 5G nationwide, as they did for all previous generations. If 5G is simply a cheaper way to support existing applications, then 5G can be deployed in cities as a cost reduction, and the LTE network can be left alone in rural areas until excess capacity is used up.

This is important enough to repeat: 5G is not about faster speeds, but about lower costs. That means that 5G will be deployed where higher capacity is needed, and LTE can be left alone in rural areas.   Many 5G networks will be limited to cities, and will not be deployed in all sites right away.

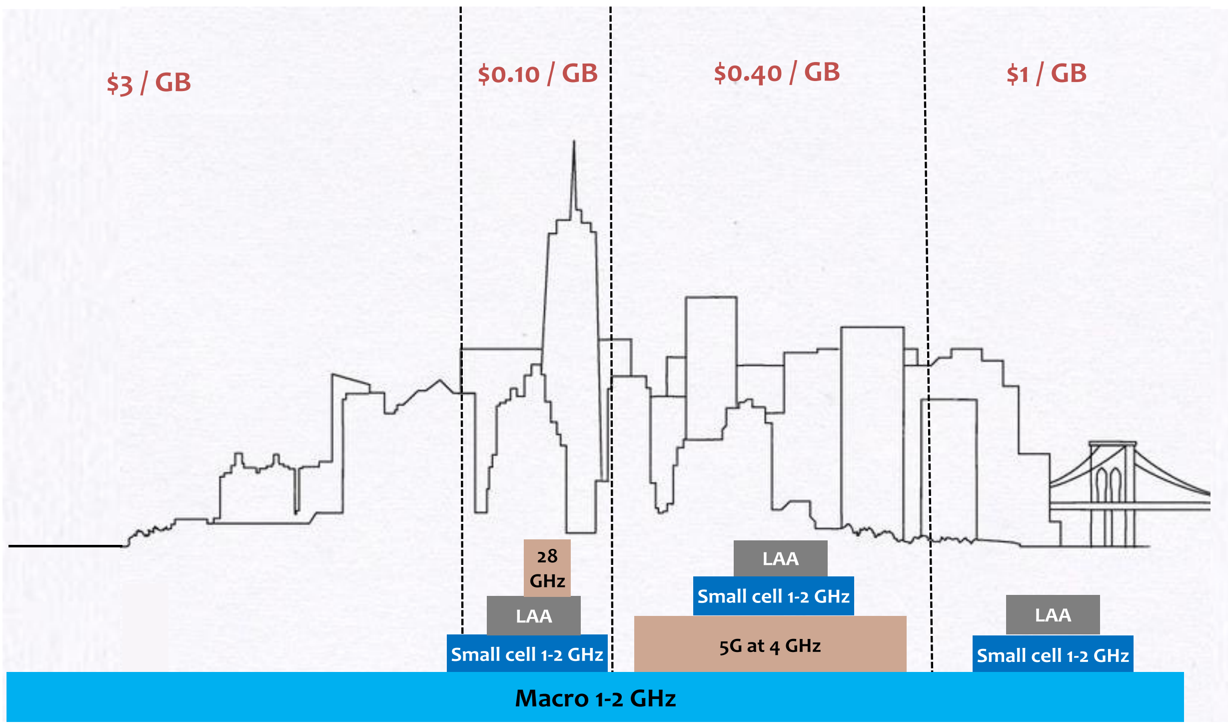

Figure 2   Using the HetNet to "right-size" the network in each neighborhood

Source: Mobile Experts

5G will include features such as Network Slicing, Virtualized RAN, Mobile Edge Computing, and new, more efficient core networks.   All of these features are worth investigation in detail.   The focus of this report centers on radio implementation, because we see the greatest potential for differentiation in the radio.

In particular, effective implementation of Massive MIMO with active-passive antenna integration will be key to achieving small size in the RRH.   Simply deploying a separate active antenna/radio unit would not be ideal, especially in markets with leased towers where the additional lease space could cost thousands of dollars per month.   The appendix at the end of this report shows multiple examples of active-passive antenna products.

Overall, we see the current implementation of Massive MIMO as good but not quite ready for prime time.   The active-passive antenna products remain huge behemoths, and interleaving various frequency bands will be required to shrink their size.   In addition, the radio configuration has not settled down yet to a small number of reasonable choices.   We see variations ranging from 4T4R to

1024T1024R, with too much fragmentation. The OEMs cannot support product lines with so much variation in frequency bands, power levels, and MIMO configurations.

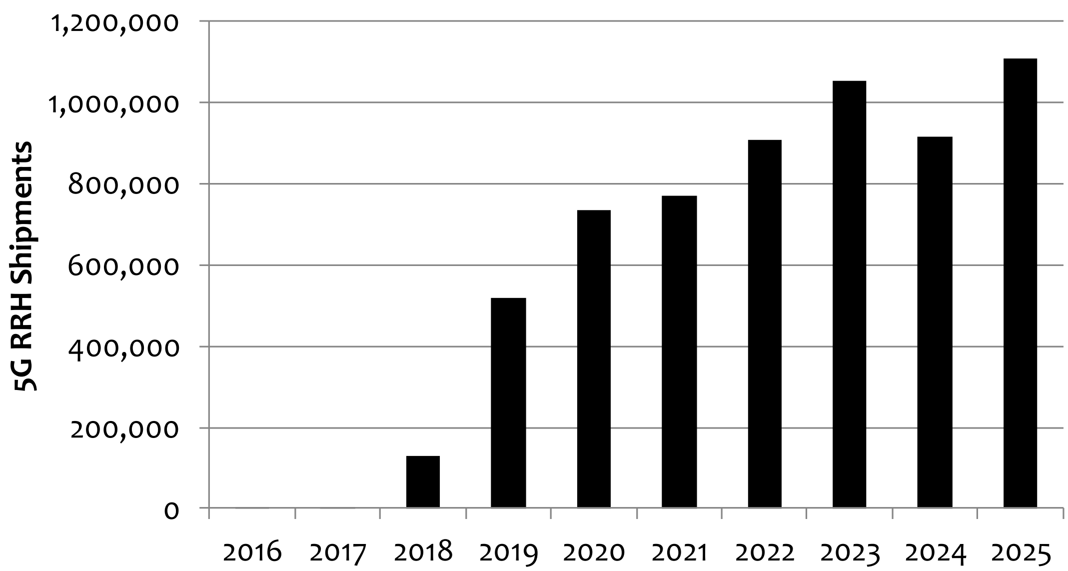

Chart 1: 5G Forecast, RRH Sectors Shipped, 2016-2025

Source: Mobile Experts

Below 6 GHz, we see a clear path to major deployment in China. We have set a forecast based on the level of activity in China and optimistic signals from China Mobile, Huawei, and others about millions of 5G base stations. However, the Chinese MIIT has not yet made an official announcement, so our forecast should be viewed as preliminary.

Outside of China, sub-6 GHz deployment is likely at large scale in countries such as Japan, Korea, Finland, and Estonia. The United States will follow when it has spectrum available. Europe will be slow to respond. We actually anticipate a slowdown in the total market in 2023-2024, when China's 5G rollout is complete, because the rest of the world may not be able to replace the Chinese volume so quickly.

Above 20 GHz, we see limited deployment in the USA for fixed wireless access, and eventually we predict deployment in Korea/Japan/China to boost capacity after the 3-5 GHz network is filled.

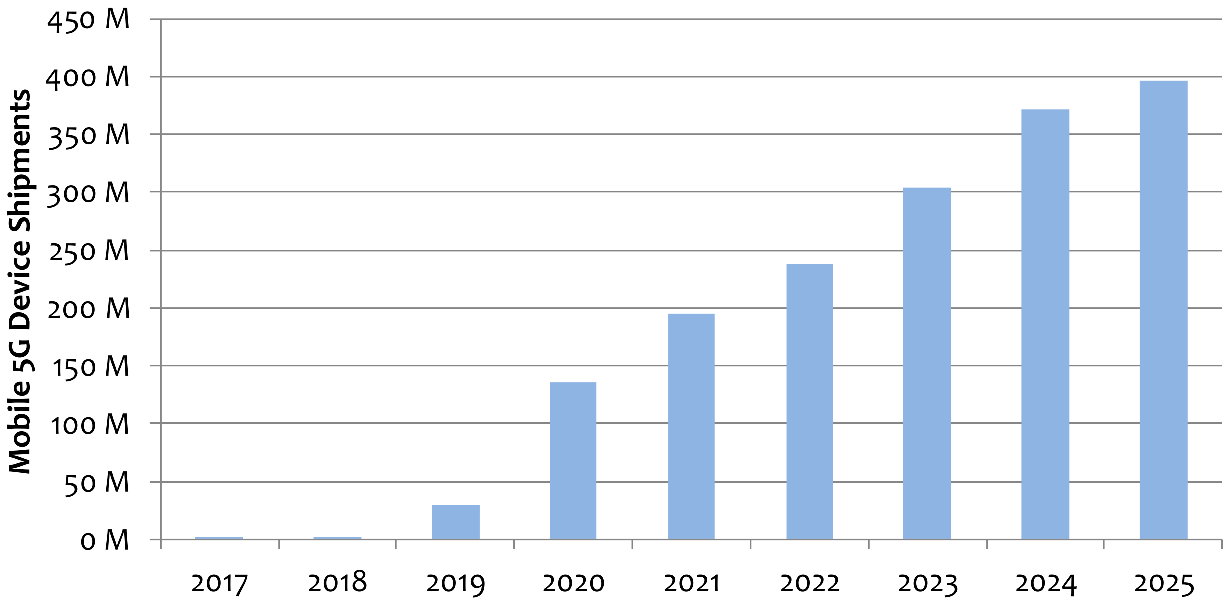

Chart 2: 5G Forecast, Mobile Devices Shipped, 2017-2025

Source: Mobile Experts

With regard to client devices, we expect Chinese networks to drive rapid adoption of 5G NR in 3.5 and 4.8 GHz bands during the 2020-2023 timeframe. When China Mobile, China Unicom, and China Telecom have 5G networks running, top-tier handset suppliers such as Apple, Samsung, and Huawei will include these bands (and 5G modems) into their handsets. That step will drive a larger number of handsets, because 5G capability will start to become available globally, even in countries with no 5G networks.

Roughly 5% of the device market will relate to tablets, PCs, and hotspots while 1-2% could possibly serve the 5G IoT market. We do not expect 5G NR to drive any significant volume in IoT, but high-throughput, low-latency applications could drive a few million devices per year by 2025.

2 TECHNOLOGY BACKGROUND

The fundamental technology for 5G communications is settling down quickly, driven by a few key operators that are itching to get started. Pre-5G infrastructure has already been introduced to the field, with early variations that at a technical level really look more like turbo-charged LTE. Not all of the variations of 5G will be ready in the first wave….but the focus of 3GPP committees and supporting OEMs has centered on a few specific cases that will be ramped up quickly.

Standards Status

The first release of the 5G NR standard is done. At 3GPP RAN meeting #78, (December 2017), the RAN working groups finalized the basics of the 5G NR waveform for TDD operation in a 100 MHz channel bandwidth. Only "non-stand alone" (NSA) operation is supported so far. In December, the basic technical parameters were frozen so that chipsets could be finalized.

The RAN committees have been moving pretty quickly, so the freeze of Release 15 specifications allows for the tape-out of chipsets and specific syntax for the firmware/software will be defined through March 2018 (known as ASN.1).

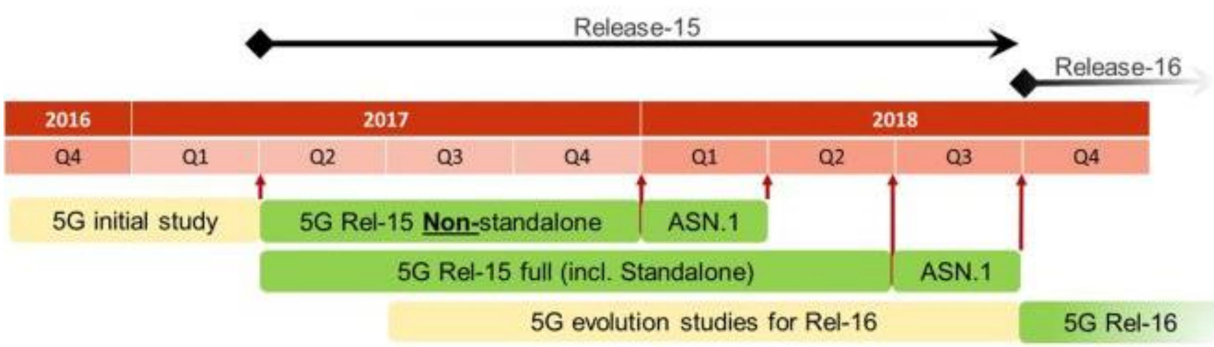

Figure 3 3GPP RAN Timeline for 5G NR standards

Source: 3GPP

Notably, the Standalone (SA) version of 5G NR will be following about a year behind the initial release. The primary impact of this will be in core networks and control signaling, as the radio hardware will not change substantially for a standalone network.

High Level Architecture Decisions

The operators involved in 3GPP have agreed to focus on a few variations of the high level network architecture, to move these options along most quickly. Here's a quick summary of some key decisions which focus current 5G NR development on specific architectural choices….keep in mind that these decisions can be altered later, as new options will be added to the 3GPP standards over time.

- The control plane and user plane will be independent. This means that control signals can come from a different eNodeB than the data payload, or can be on a different band.

- The Central Unit and Digital unit will be split, so baseband processing functions and some core network functions can be independent. The impact of this split is not clear at a business level because there's no consensus on how this split/interface will work, so we don't expect an interoperable interface which would allow for competition to enter here.
- The "Option 3" and "Option 2" combinations of radio networks and core networks are the focus through March 2018. The next priorities will be Option 4 and Option 7x.

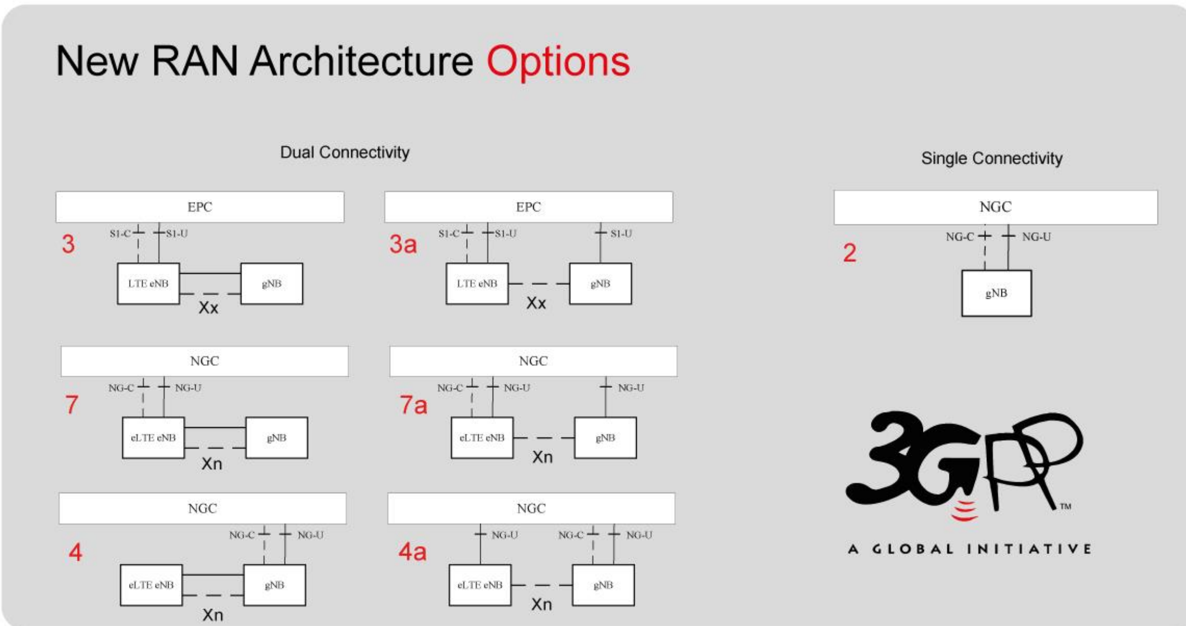

Figure 4 RAN Architecture options

Source: 3GPP

5G NR Operating Bands and Channel Bandwidths

The RAN committees have worked hard to accommodate operators with a wide variety of spectrum, so 26 different frequency bands have already been identified for 5G NR operation. Note that not all of these are ready for all 5G NR features, so even though the frequency band has been identified, for example Massive MIMO in FDD bands will require some additional work in order to "close the loop" on channel estimation.

Having said that, the current state of 3GPP standards makes it possible to deploy 5G NR in a simple configuration in FDD frequency bands in the short term. As an example, T-Mobile USA should have fairly clear path to deployment of 5G NR in the 600 MHz FDD band, despite only having 30 MHz of spectrum. In some cases, with limited channel size (such as 5 MHz wide channels, only the 15 kHz OFDM sub-channel spacing option is allowed).

NR Operating Band	Uplink band			Downlink band			Duplex Mode	Channel Bandwidth Options
n1	1920 MHz	–	1980 MHz	2110 MHz	–	2170 MHz	FDD	5-20 MHz
n2	1850 MHz	–	1910 MHz	1930 MHz	–	1990 MHz	FDD	5-20 MHz
n3	1710 MHz	–	1785 MHz	1805 MHz	–	1880 MHz	FDD	5-30 MHz
n5	824 MHz	–	849 MHz	869 MHz	–	894MHz	FDD	5-20 MHz
n7	2500 MHz	–	2570 MHz	2620 MHz	–	2690 MHz	FDD	5-20 MHz
n8	880 MHz	–	915 MHz	925 MHz	–	960 MHz	FDD	5-20 MHz
n20	832 MHz	–	862 MHz	791 MHz	–	821 MHz	FDD	5-20 MHz
n28	703 MHz	–	748 MHz	758 MHz	–	803 MHz	FDD	5-20 MHz
n38	2570 MHz	–	2620 MHz	2570 MHz	–	2620 MHz	TDD	5-20 MHz
n41	2496 MHz	–	2690 MHz	2496 MHz	–	2690 MHz	TDD	10-100 MHz
n50	1432 MHz	–	1517 MHz	1432 MHz	–	1517 MHz	TDD	5-90 MHz
n51	1427 MHz	–	1432 MHz	1427 MHz	–	1432 MHz	TDD	5 MHz
n66	1710 MHz	–	1780 MHz	2110 MHz	–	2200 MHz	FDD	5-40 MHz
n70	1695 MHz	–	1710 MHz	1995 MHz	–	2020 MHz	FDD	5-25 MHz
n71	663 MHz	–	698 MHz	617 MHz	–	652 MHz	FDD	5-20 MHz
n74	1427 MHz	–	1470 MHz	1475 MHz	–	1518 MHz	FDD	5-20 MHz
n75	N/A			1432 MHz	–	1517 MHz	SDL	5-20 MHz
n76	N/A			1427 MHz	–	1432 MHz	SDL	5 MHz
n78	3300 MHz	–	3800 MHz	3300 MHz	–	3800 MHz	TDD	5-20 MHz
n77	3300 MHz	–	4200 MHz	3300 MHz	–	4200 MHz	TDD	10-100 MHz
n79	4400 MHz	–	5000 MHz	4400 MHz	–	5000 MHz	TDD	40-100 MHz
n80	1710 MHz	–	1785 MHz	N/A			SUL	5-30 MHz
n81	880 MHz	–	915 MHz	N/A			SUL	5-20 MHz
n82	832 MHz	–	862 MHz	N/A			SUL	5-20 MHz
n83	703 MHz	–	748 MHz	N/A			SUL	5-20 MHz
n84	1920 MHz	–	1980 MHz	N/A			SUL	5-20 MHz

Figure 5   5G NR Frequency Bands and Channel Bandwidths

Source: 3GPP

In short, the 3GPP committees have met their goal to freeze the MAC and PHY requirements, getting the chipsets moving toward production during December 2017. The "Phase 1" activities are continuing to fill in additional variations, but the simple upgrade of LTE to 5G is underway.

Phase 2 activities are targeted to upgrade 5G networks to meet the expectations of the ITU in their IMT-2020 goals, with release in late 2019. From a commercial point of view, the ITU specification is arbitrary and fairly meaningless, so these improvements will be implemented on a case-by-case basis.

Radio Access Architecture Decisions

The key improvements in the RAN architecture for 5G NR include the following features. Note that some of these features are now being pulled into LTE networks, as improvements such as Massive MIMO can work independently of the waveform itself.

1. Massive MIMO: Also known as full-dimension MIMO, FD-MIMO, or 3D-MIMO, the use of more than 8 antenna elements per sector allows for a dramatic increase in spectral efficiency, because the spectrum can be re-used effectively by breaking the sector into narrow beams. Massive MIMO requires good channel models, which have now been proven for TDD operation but are not mature for FDD networks at this point in time.
2. OFDM with Options: In the New Radio frame structure, the number of subcarriers, bandwidth, and subcarrier spacings are flexible. The subcarrier spacing specified so far ranges from 15 KHz to 60 kHz. 3GPP has decided to adopt CP-OFDM, at least up to 52.6 GHz, with the same waveform in both directions. The cyclic prefix scales from 4.69 microseconds (at 15 kHz subcarrier spacing) to 1.17 microseconds at 60 kHz subcarrier spacing.
3. DFT-Spread OFDM in uplink will be allowed, resulting in a lower peak-to-average power ratio (PAPR) for single stream transmissions. (Overall, the intention is to modify OFDM to improve out-of-band spurious emissions, keep Peak-to-Average Ratio (PAR) as low as possible, and allow for very flexible use of spectrum, from ultra-reliable low latency communications to very high throughput links.)
4. 5G NR uses low-density parity-check codes for the data channel, and polar codes for an efficient control channel. The details are not important at a business level, but these codes represent an improvement in energy efficiency for the infrastructure and devices.

Massive MIMO (M-MIMO, FD-MIMO, 3D-MIMO)

The simplest way to think of this: Massive MIMO is a way to convert a typical 3-sector site to a 12-sector or 24-sector site, using narrow antenna beams… and this can increase the theoretical spectral efficiency from 2bps/Hz to 8 or 16 bps/Hz. The practical implementation of Massive MIMO in a planar array of antennas means that the sectorization is very flexible, and the beams can move around as needed to "follow" users or groups of users.

In practice, the spectral efficiency gain is lower when users are clumped closely together, due to the limitations of beamwidth in real-world antennas. The higher the Massive MIMO order, (256T256R and higher), the tighter the beam can be….but of course the higher complexity has its drawbacks in terms of power and size.

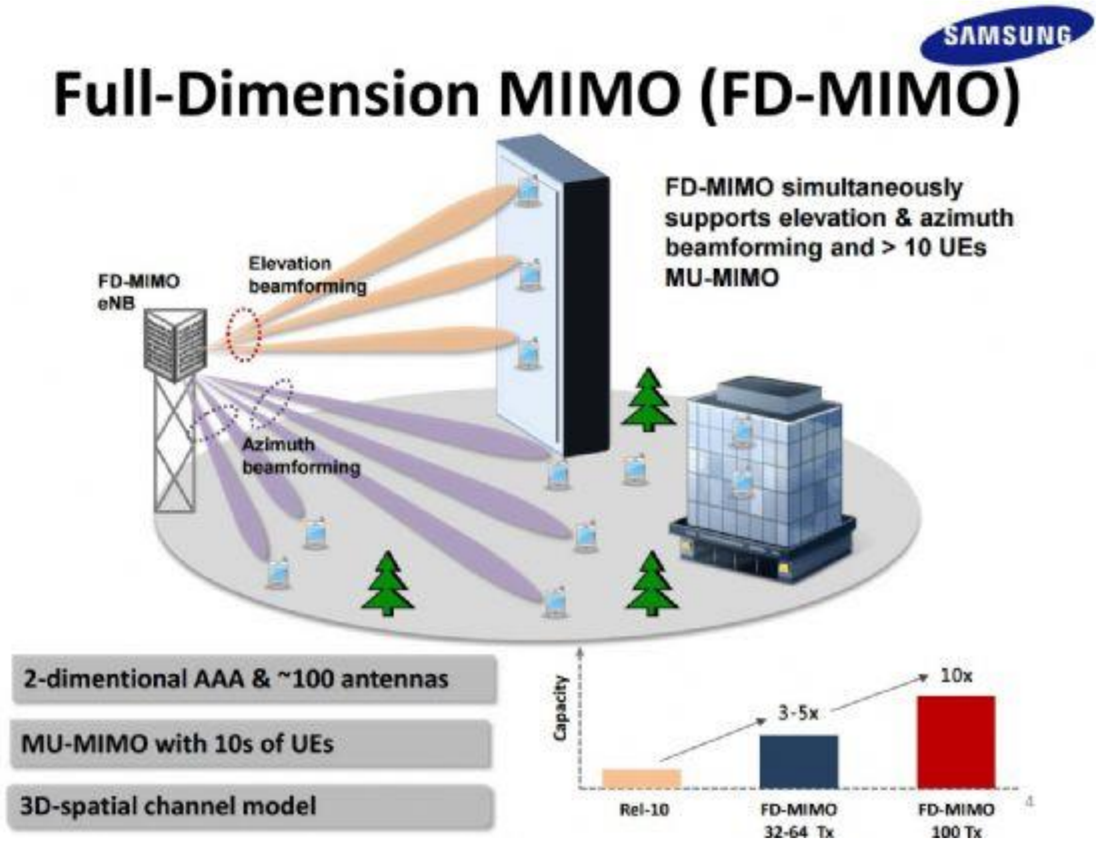

Figure 6 FD-MIMO Illustration

Source: Samsung

The physical realization of Massive MIMO includes some basic characteristics:

- An Active Antenna System, with beamforming using multiple antenna elements. In general, the number of elements must be 4X the number of beams actually employed, in order to get effective separation between beams. So, a 64T64R m-MIMO array can probably handle up to 16 beams effectively.
- Integrated Antenna Radio (IAR) implementation. Large arrays would be impractical if we relied on a technician to connect hundreds of coaxial cables between the antenna and the radio. Instead, the radio and the antenna array must be tightly integrated. This is especially important for millimeter-wave radios, where any transitions or transmission lines between amplifier and antenna would be detrimental. The rest of the RRH (ASIC or FPGA) might be located elsewhere, but all major OEMs are using full integration of the RRH and antenna for 16T16R systems and higher.
- MU-MIMO. As we mentioned above, an array can support one MIMO stream for every 4 antenna elements, so a large array (between 64T and 256T) can support between 16 and 64 streams of data. Multi-User MIMO allows these data streams to be allocated to users in flexible configurations… in a simple example with 16 streams, four users can enjoy 4x4 MIMO, or eight users can get 2x2 MIMO.

CP-OFDM

Adding a Cyclic Prefix to the OFDM waveform can reduce inter-symbol interference and allows linear convolution for channel estimation. The industry has now settled on a consensus that use of a CP will improve performance, with a simultaneous improvement in out-of-band emissions.

Subcarrier Spacing	15 kHz	30 kHz	60 kHz	15 x 2^n kHz
OFDM symbol duration	66.67 microsec	33.33 microsec	16.67 microsec	66.67/2^n microsec
Cyclic prefix duration	4.69 microsec	2.34 microsec	1.17 microsec	4.69/2^n microsec
OFDM symbol including CP	71.35 microsec	35.68 microsec	17.84 microsec	71.35/2^n microsec
Number of OFDM symbols per slot	7 or 14	7 or 14	7 or 14	14
Slot duration	500 microsec or 1 msec	250 microsec or 500 microsec	125 microsec or 250 microsec	1 ms/2^n

Figure 7   Details of CP-OFDM implementation

Source: Ericsson

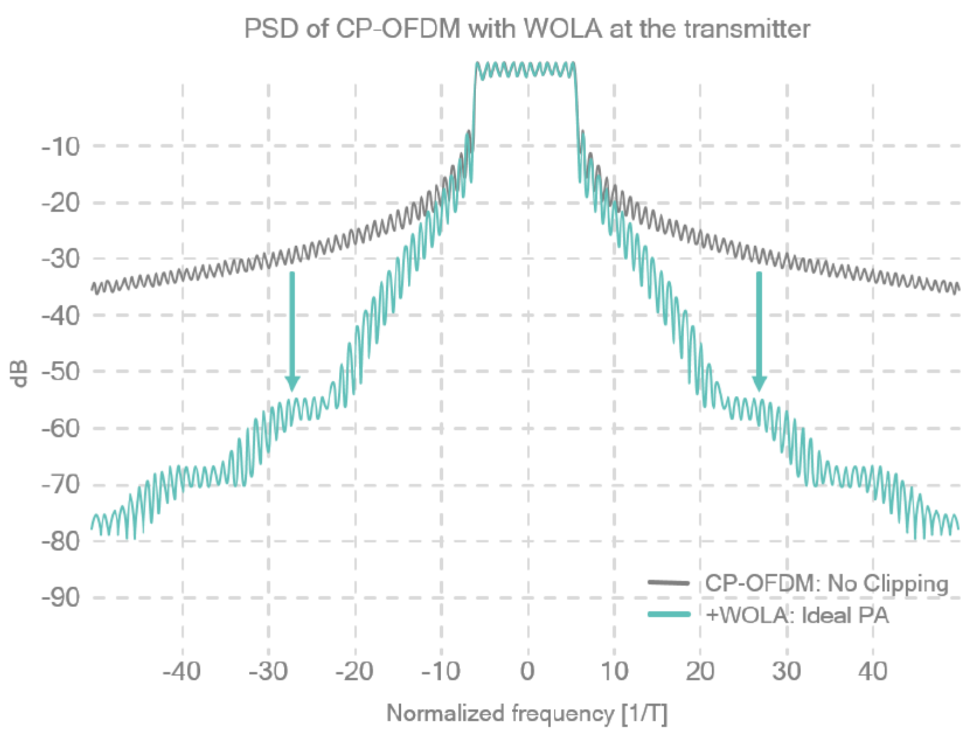

Figure 8   Out-of-band emissions for CP-OFDM

Source: Qualcomm

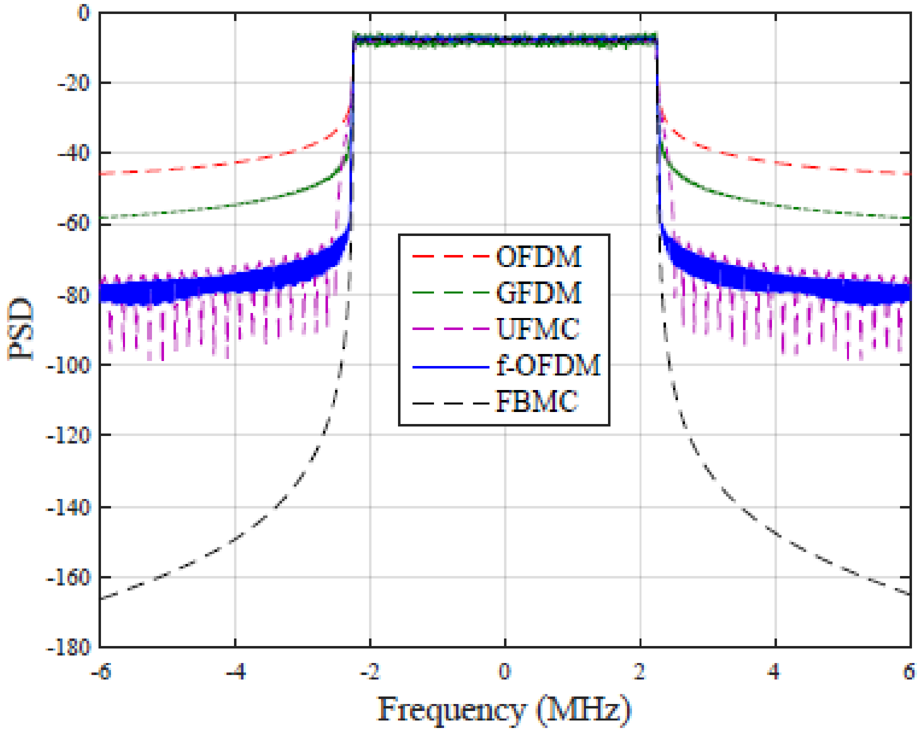

Figure 9 Out-of-band emissions simulation for OFDM, GFDM, UFMC, f-OFDM, FBMC

Source: Huawei

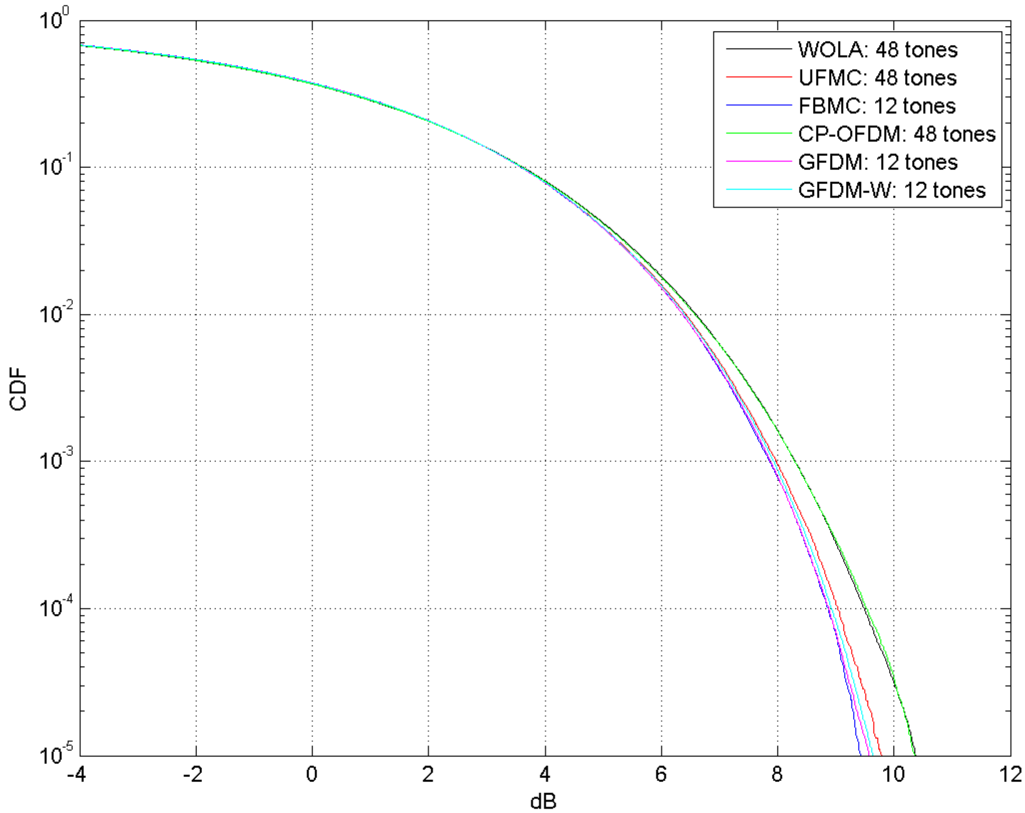

Figure 10   Peak-to-Average Ratio for OFDM, GFDM, UFMC, f-OFDM, FBMC

Source: Qualcomm/3GPP

Migration from NSA to SA

All of the initial 5G NR networks will use the Non-Standalone configuration, using LTE core networks and LTE control channels to govern the use of a 5G NR data channel. This is the quickest way to get going, and in fact the 3GPP committees focused their efforts on "Option 3" and "Option 3a" in order to get the standard completed a bit earlier than expected.

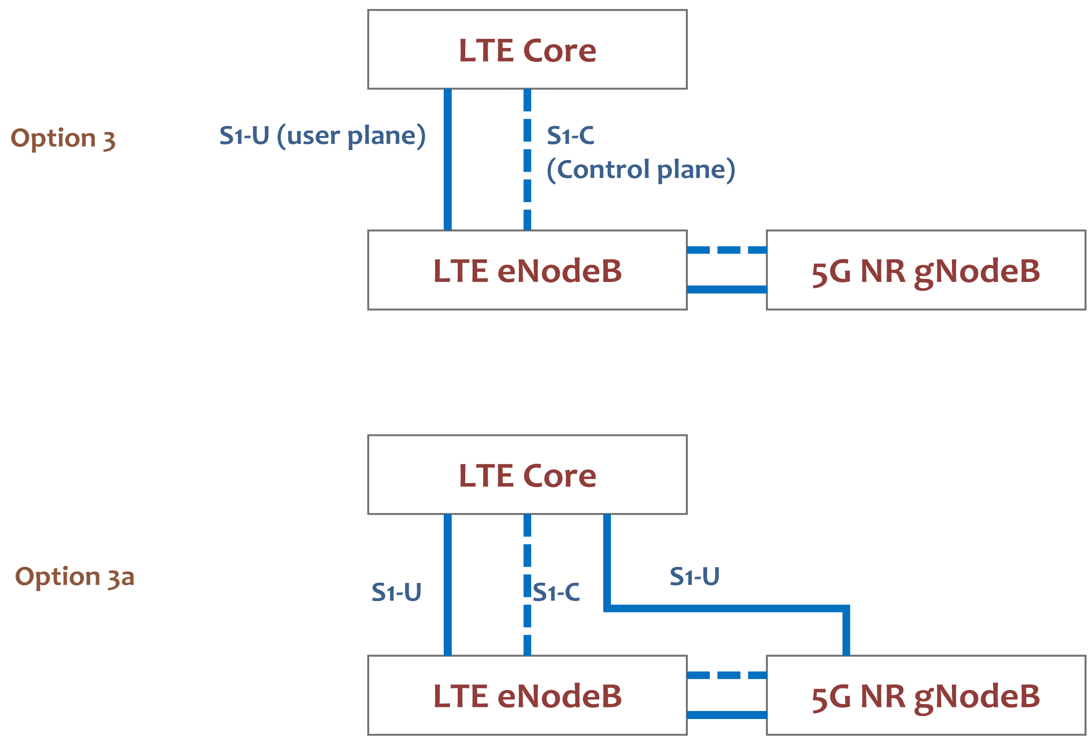

Figure 11 RAN Architecture expected for NSA networks

Source: 3GPP/Mobile Experts

In the NSA format, 5G NR is simply an aggregation layer, where user plane data runs through the 5G NR "g Node B" in addition to user plane data through the LTE eNodeB. This way, it can be treated in a way that's similar to Wi-Fi aggregation, where the 5G layer is only shuttling user plane packets and the LTE network is putting them together.

Note that we expect the NSA configuration to be a barrier to entry for network equipment vendors to "steal" business from each other. If one vendor controls the LTE hardware, then he has an advantage in bidding for 5G. This is not perfect, as we have seen with Samsung at Verizon, but it's one more barrier to entry in vendors attempting to flip a 4G customer to a new supplier in the 5G cycle.

In the Stand-alone scenario, the primary change is the addition of a 5G Next Generation Core network and the network slicing feature. The 3GPP committees have developed multiple options for various radio scenarios, but our primary defining trait for "stand alone" comes down to the use of a 5G core network.

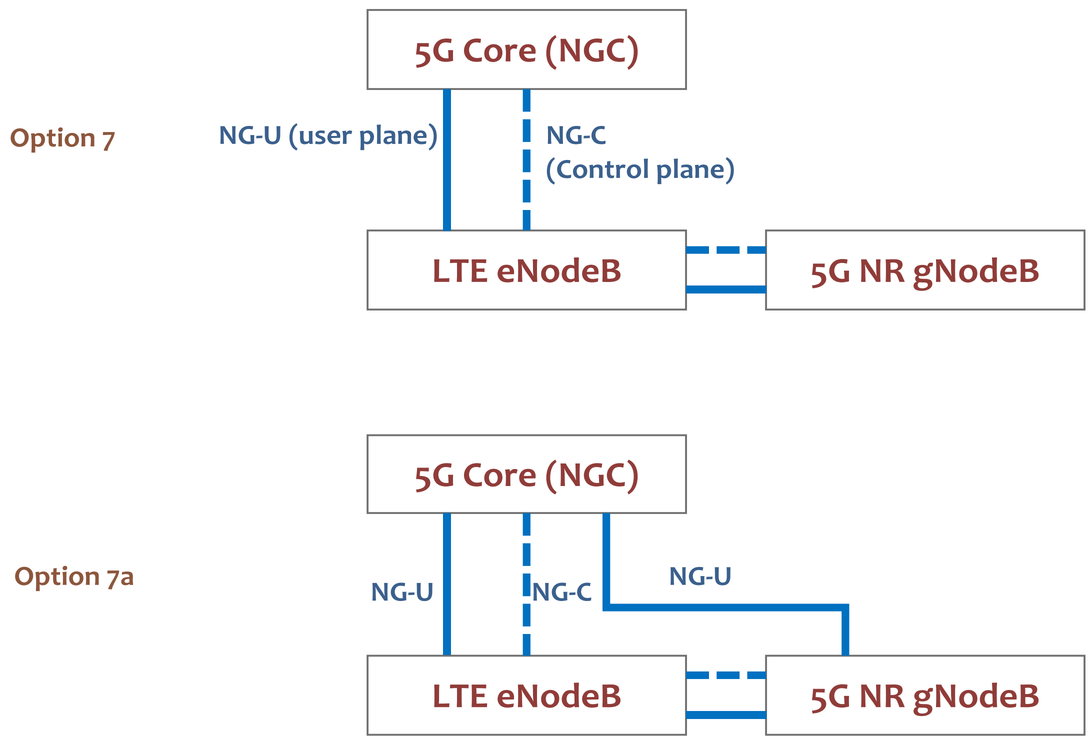

Figure 12 RAN Architecture expected for SA networks

Source: 3GPP/Mobile Experts

A truly "stand alone" network, in the complete sense of this phrase, does not rely on any LTE resources either at the radio level or at the core network. We are expecting the cable operators in the USA market to deploy "option 2" standalone networks, with a 5G next generation core network and 5G radios—without any LTE. Note that China Mobile has announced the use of a standalone network from the beginning—so this should have a major impact on future adoption by others as well.

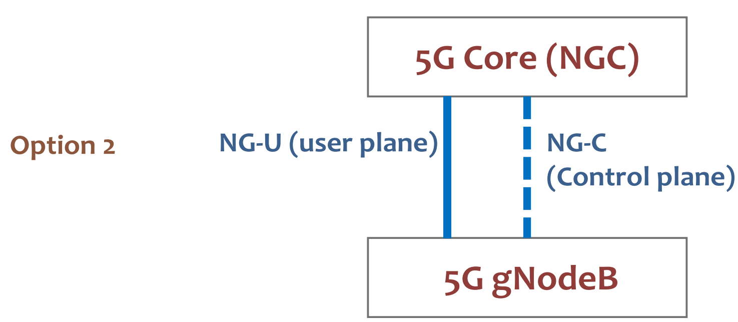

Figure 13 Simpler architecture for single-band Stand Alone 5G networks

Source: 3GPP/Mobile Experts

3 SPECTRUM

Almost any mobile band can be used for 5G, now that 3GPP has designated channel bandwidths down to 5 MHz. (we expect even more narrow channels in the future as well). Of course, the existing 800 MHz – 2.5 GHz bands are highly utilized today for 2G/3G/4G networks, so most operators are looking for fresh blocks of spectrum to initiate 5G service.

At a high level, it's clear that 5G networks will fall into a few categories:

- Licensed-band networks below about 6 GHz will use spectrum blocks that range from 5 MHz to 200 MHz wide. In most cases for 5G NR, operators are looking at bands that offer 100-200 MHz of contiguous spectrum, in order to get the biggest impact from the 5G NR waveform and from Massive MIMO.
- Unlicensed bands below 6 GHz (the UNII bands, 5150 to 5925 MHz) could be used for 5G NR, just as LTE can be used in these bands today. In addition, the CBRS band (3550-3700 MHz) in the USA is a possibility for lightly-regulated spectrum that could add a big enough chunk for a 5G channel.
- Licensed networks above 20 GHz can cover bandwidths between 200 MHz and 1 GHz so far, and we expect some new mm-wave frequency bands to offer as much as 5 GHz of bandwidth. In the short term, we expect that the 28 GHz band will get the most traction, but eventually the 70-90 GHz range could be important as very wide bands could come into play.
- Unlicensed operation at 60 GHz remains a possibility for 5G NR, but we don't expect any serious development in this direction because mobile operators are more focused on licensed bands.

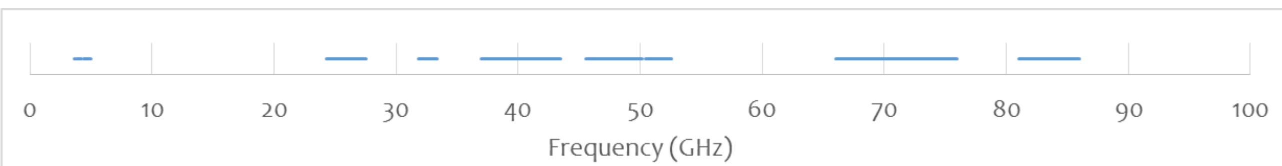

Figure 14. Spectrum blocks considered at WRC-15 for 5G

Source: WRC-15

Licensed and Unlicensed bands below 6 GHz

The global picture is starting to become clear for 5G deployment. Many operators worldwide are working toward a level of harmonization, settling on the 3.5 GHz band as a common baseline to promote economy of scale in the supply chain.

- Japan: The Japanese Ministry of Internal Affairs and Communications (MIC) has recently changed its 5G licensing rules to open up more competition between its three major carriers and other non-telecom players. We expect MIC to grant spectrum licenses over the next few months, in preparation for the Tokyo 2020 Olympics. MIC has not made an official announcement on the spectrum to be licensed, with possibilities ranging from 3600-4200 MHz and 4400-4900 MHz. The most credible reports from Japanese operators expect that the 4.5-4.8 GHz band will be allocated for 5G in blocks of 100 MHz each.

- Korea: South Korea will begin a 5G auction in June 2018, with about 100 MHz for each of the three major carriers in the 3400-3700 MHz band. This is a significant acceleration of the timeframe, as previous announcements aimed at licenses in 2019.
- China: The Ministry of Industry and Information Technology (MIIT) has set aside the 3.3 to 3.6 GHz band, as well as 4.8-5 GHz. The band from 3.6 to 4.2 GHz may be introduced later. . Rumors indicate that China Mobile is likely to get the 4.8-5 GHz block, while China Unicom and China Telecom are likely to get spectrum in the 3.3 to 3.6 GHz range as well as authorization to use the 700 MHz or other 900 MHz-2.5 GHz spectrum for 5G NR.
- Europe: Various countries in Europe are lining up in the 3.4-3.8 GHz band with 5G spectrum plans. Ireland, Italy, Spain, and Finland have designated bands within this range as possible upcoming licenses.
- United States: The bands between 3.3-3.5 GHz and 3.7-4.2 GHz are possibilities for 5G allocation, but are also heavily sought after by Google and other unlicensed users. No decisions have been made by the Federal Communications Commission on these bands yet, so the only C-band spectrum possible in the USA is the 3.55-3.7 GHz shared spectrum, which will be licensed over the next 6-12 months through a new Priority Area Licensing process. It's not clear whether US operators would deploy LTE or 5G NR radios in this band.
- Note that ZTE and Huawei have demonstrated asymmetric use of 5G spectrum, with 3.5 GHz used as the downlink band and 1.8 GHz or other bands used for uplink. The configuration of LTE would be based on TDD, despite the separate uplink and downlink bands. Support for this proposal is growing because it could benefit the link balance greatly.

Licensed and Unlicensed bands above 20 GHz

- USA: The focus for 95% of development efforts today is at 28 GHz, with active commercial deployment taking place in the 27.5-28.35 GHz band in the USA with Verizon Wireless. American operators also have licenses to FDD spectrum at 24 GHz, as well as TDD spectrum at 37-40 GHz, so we expect deployment of 5G fixed-wireless services in these bands as well.
- In Korea, the entire 26.5 – 29.5 GHz band is available for 5G services and is expected to be auctioned in June 2018 (probably 1 GHz to each of the three operators).
- Japan: Operators are conducting trials at 27.5-29.5 GHz. With the high density of the Japanese network, we're expecting the C-band deployment to be followed by hotspot 28 GHz deployment in the 2022-2023 timeframe.
- China: The 24.75-27.5 GHz band and 37-42.5 GHz bands are under consideration by the MIIT for 5G trials. The next set of decisions will take place after some trial results come available.
- Europe: Individual countries such as Sweden are expected to award licenses at 28 GHz over the next two years. Also, European regulators have designated a "pioneer band" at 24.25 – 27.5 GHz as a 5G band, and another likely band at 40.5-43.5 GHz.
- 60 GHz: The unlicensed band at 60 GHz is tempting, with a wide block of spectrum that is free. The US Government has made a ruling that this use of the 60 GHz band would be authorized, but other countries have been silent on this issue so far. The supply chain is not convinced, as we have not seen a strong R&D push in this direction.

The Role of the WRC

The WRC-15 meeting was intended to identify specific bands and to make firm decisions to harmonize allocation of key bands below 6 GHz to mobile telecom services. There was some success along these lines, although the ITU did not achieve its goal of allocating more than 1340 MHz of spectrum to IMT services by 2020. Here are some notes on specific bands:

- 470-694 MHz spectrum was not uniformly adopted with some regions (specifically EMEA region countries) sticking with terrestrial broadcasting.
- 694-790 MHz spectrum was more successful, with movement toward harmonization in EMEA and APAC countries to match the Americas.
- The 1427-1518 MHz band (which is already used for telecom in Japan) was moved one step closer to IMT services in the Americas and Asia, but not in Europe.
- 3300-3400 MHz spectrum was identified for mobile services for the first time with 33 countries in Africa, 6 in Latin America, and 6 in APAC joining together.
- 3400-3600 MHz spectrum has reached nearly global designation for mobile telecom.
- 3600-3800 MHz is not as globally recognized, with some countries opting for a smaller 3600-3700 MHz band.
- The 3800-4200 MHz band did not get designated for mobile telecom in this meeting.
- Similarly, 4400-4500 MHz did not get designated for mobile services.
- The 4800-4990 MHz band was designated for mobile services.

Overall, this story is not complete because each country can simply choose to use any band for mobile services as it sees fit.

Notably, the WRC discussion designated all of the bands below 6 GHz as “4G” bands, and most of them have already been identified in a few countries for 4G services. We expect that the designated LTE bands (up to 3700 MHz) will use LTE, wherever channel bandwidths are 20 MHz. Wider channel availability (such as the 3.5 GHz band in China) will migrate to 5G NR. Newer “5G” services with wider channel bandwidths are likely to be introduced between 3100 MHz and 4990 MHz In particular. For 5G below 6 GHz, we will be tracking the bands at 3400-3600 MHz, 3800-4200 MHz, 4400-4500 MHz, and 4800-4990 MHz as the most likely blocks.

The millimeter-wave bands proposed at WRC-15 include:

- 24.25 – 27.5 GHz
- 31.8 – 33.4 GHz
- 37.0 – 43.5 GHz
- 45.5 – 50.2 GHz
- 50.4 – 52.6 GHz
- 66.0 – 76.0 GHz (note this is not aligned with the USA’s study of 64-71 GHz)
- 81.0 – 86.0 GHz

Notably, the 28 GHz band that has emerged as the primary pre-5G frequency band in the USA and Korea is not on the WRC list, because the ITU has the 28 GHz band listed nominally as a band for fixed services. Each country will need to decide on its own to designate 28GHz as a mobile band.

4 REGULATORY REQUIREMENTS

Many kinds of regulatory requirements can impact the development of 5G, and each regulatory entity creates rules for different reasons. Here's a basic overview of the types of requirements that 5G networks will contend with:

- Interference regulations on satellite/terrestrial/mobile use of spectrum;
- Interference rules to protect competing operators from each other;

Interference over wide bands: Will 5G interfere with satellites?

The process of regulating the use of radio equipment usually begins with the government's overall philosophy about how to segregate different kinds of radio systems. Most advanced economies have set aside key bands for terrestrial systems, and another set of bands for satellite systems. The reason is simple: satellite transmitters are relatively weak and the receivers in low-cost satellite receivers are not perfect.

As an example, consider GPS receivers at 1.575 GHz. Most mobile and other terrestrial communications systems have been cleared out of the 1.5 GHz band because the GPS signals coming from the satellite are very weak, and the low-cost GPS receivers in billions of devices depend on low interference levels in the spectrum surrounding the GPS band. It's not enough to simply transmit at 1.579 GHz, because the receiver filters are not sharp enough to reject a signal that is near the transmitted signal. For this reason, the ITU and each government identify entire sections of the spectrum that are dedicated to similar services.

For mobile 5G, this concern can be overcome in many cases. For example, the 28 GHz band is currently designated as a band for fixed terrestrial services, but multiple governments have indicated their willingness to waive this requirement to allow mobile usage.

On the other hand, satellite bands are a concern for mobile 5G. L-band (1.5 GHz), C-band (4 GHz), and Ka-band (18-26 GHz) satellite systems will all require fairly clean surrounding spectrum, so government authorities must proceed with caution and a lot of testing in considering adjacent mobile services. For example, the -28 dBc ACLR requirement that has been selected by 3GPP will be okay for interference between two 5G services. *But will the -28dBc suppression of out-of-band emissions be enough to protect satellite receivers from nearby 5G users?* Nobody knows the answer to this question yet.

Interference over narrow bands: Will 5G operators interfere with each other?

As we predicted last year, government agencies are now starting to allocate 5G spectrum for competing operators in adjacent bands. The Japanese government plans to license the 4.5 to 4.8 GHz band in three equal blocks of 100 MHz each, without guard bands in between.

As a result, the mobile operator needs to consider whether a guard band is necessary for effective 5G performance. Huawei recommends 25 MHz guardband (!) for asynchronous TDD-based 5G NR networks. In this scenario, there are some significant differences with the famous "near-far" problem that confronted 2G through 4G systems:

1. Beamforming in the 5G transmitters results in a reduction in overall interference. From a statistical point of view, the directional beams eliminate interference in both infrastructure and client devices. This factor is tempting, because it suggests that interference levels are lower.
2. In cases where a competing transmitter lies in the same direction as a faraway transmitter, however, the relative interference levels in a 5G system can be higher than 2G through 4G systems. In Figure 15 below, the "aggressor" signal can block the desired signal in the "victim" receiver.

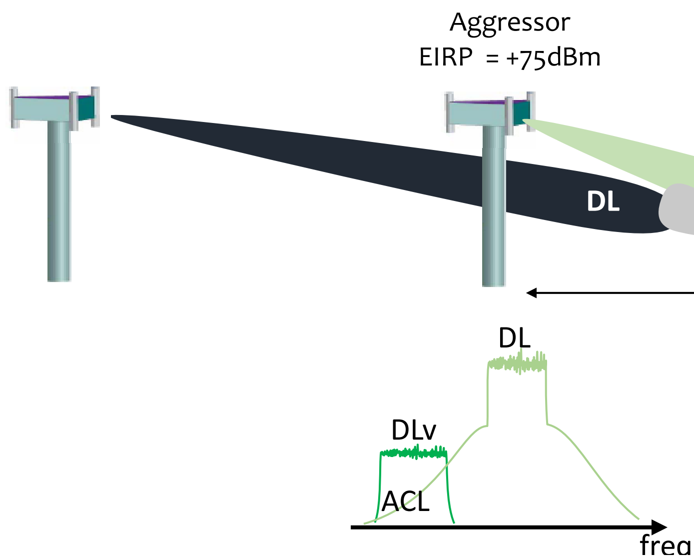

Figure 15. Anticipated mobile 5G interference scenario—Base Station Aggressor

Source: Qualcomm/3GPP

3. TDD-based systems can also experience interference in a similar scenario, where the "aggressor" UE transmits in very close proximity to the "victim" receiver. Because mobile 5G is set up as a TDD technology, uplink signals on the competing network can be transmitted during a downlink frame for the victim. Additional field testing is necessary to assess the potential impact of this scenario.

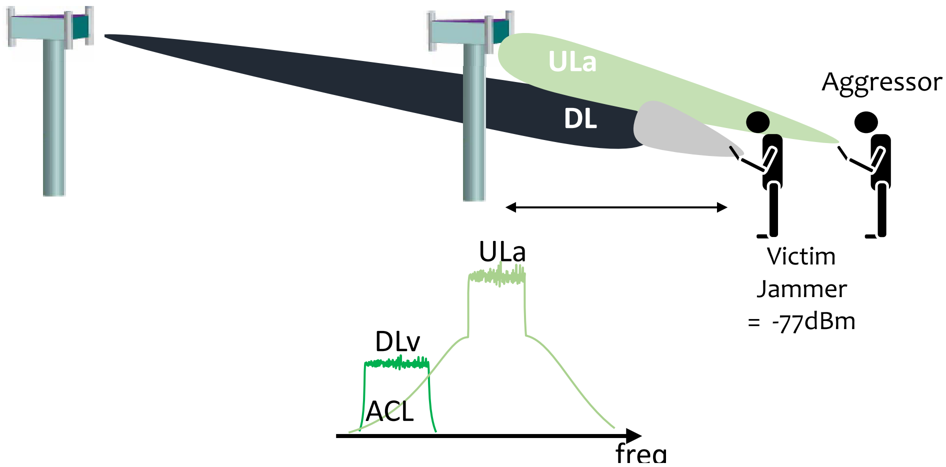

Figure 16. Anticipated mobile 5G interference scenario—UE aggressor

Source: Qualcomm/3GPP, modified by Mobile Experts

5 System Level Implementation—Strategic Impact

For 2018-2020 deployment of 5G, we expect the high-level system architecture to be fundamentally an extension of LTE. This could offend 5G purists, but here's what we mean:

- Non-stand alone (NSA) networks will use an LTE core network;
- NSA networks will use control signaling on LTE, in an existing LTE band;
- 5G NR will be used for the data plane only, and in many cases aggregated with data in an LTE data channel;

Over time, of course, the LTE core network will be replaced by a 5G EPC, which is likely to be virtualized and extremely efficient. Non-stand alone networks will give way to a stand-alone configuration, which will encourage more competition between the major network vendors. As we transition to SA networks, we expect new customers (non-traditional telcos) to use 5G in competition with existing mobile carriers.

Along the way, there are some high level system features that are often discussed, but the true impact of each feature is not well understood. This section serves to provide some context, with an explanation of the expected strategic impact of each aspect of 5G.

The 5G Waveform

In previous generations, the change in the air interface (with a focus on channel bandwidth, frame structure, numerology, etc) was the single most critical change. From 2G to 3G, spectral efficiency improved from 0.1 to about 0.5 bps/Hz. In the transition to 4G, we moved up to 1-2 bps/Hz. This basic change resulted from more effective use of coding gains to pack more information into a narrow slice of spectrum.

In 5G deployment, we only expect about 15% gain from the waveform itself. There are improvements in terms of the LPDC control channels and the flexible frame structure. But in LTE, the industry had progressed nearly to the Shannon limit for spectral efficiency in a mobile environment, and pure spectral efficiency gains are getting more difficult to squeeze out of the radio. Experts that we've interviewed have estimated that 5G NR will achieve between 10% and 20% improvement over LTE in terms of spectral efficiency, given identical MIMO configuration and signal-to-noise ratio.

Massive MIMO

The impact of Massive MIMO will be much more meaningful than the 5G NR waveform itself. In fact, TD-LTE operators have already deployed roughly 20,000 Massive MIMO upgrades during 2016-2017 because the gain is significant and it's not too expensive.

In all trials to date, including TDD, FDD, sub-6 GHz and mm-wave, Massive MIMO boosts the spectral efficiency from the typical 2.5 bps/Hz level to a much higher value. In FDD bands, where the frequencies are lower and thus wavelengths are longer, the vendors are implementing 16T16R and 32T32R configurations, and have no current plans to move higher because the antenna system would grow too large. In these cases, spectral efficiency reaches about 6 bps/Hz in field testing.

In TDD applications of 5G NR, the trials have focused on more complex arrays. Because TDD bands are generally higher in frequency, this can be practical. A 64T64R radio system yields spectral efficiency in the range of 8 bps/Hz, and bigger arrays have pushed much higher. We anticipate that in mm-wave bands with 4x256T panels, spectral efficiency of 10 bps/Hz could be possible, using the combination of 4x4 MIMO and the high-gain antenna isolation.

We believe that the implementation of Massive MIMO arrays and radio hardware will become a major area of differentiation between the equipment vendors. These products are NOT currently sized for optimal placement on a tower, and when Massive MIMO arrays are combined with passive antennas the initial result has been a Frankenstein antenna, three meters tall. The industry needs to get more creative in this area to reduce size, power consumption, and weight.

Vendor	Band	Antenna Configuration	RF Power	Size
Huawei	3.5 GHz/200 MHz	64T64R	200 W	1520 x 395 x 180 mm
Huawei	3.5 GHz/200 MHz	32T32R	200W	1140 x 395 x 180 mm
Huawei	2.6 GHz/40 MHz and 3.5 GHz/100 MHz	32T + 32T	160W total (60W + 100W)	799 x 395 x 180 mm
Nokia	2.5 GHz	64T64R	120W	Estimated 1000 x 400 x 150 mm
Ericsson	2.6 GHz/50 MHz and 3.5 GHz/unknown	32T + 32 T	100W each	Estimated 700 x 450 x 150 mm
Samsung	2.6 GHz/100 MHz	64T64R	+54 dBm	330 x 231 x 152 mm

Figure 17. Comparison of various RRH/AAS products below 6 GHz

Source: Various vendors and Mobile Experts estimates

In the mm-wave bands, the size comparison may not be as critical, but we see some differences between vendors here as well. In particular, we believe that the differentiation between vendors will come down to the level of RF power. Samsung has led the market with about +55 to +56 dBm EIRP for the past two years, and Ericsson has recently broken out of its previous performance plateau at +48 to +50 dBm, to achieve higher EIRP as well. Nokia has lower EIRP in our table, but to be fair, Nokia has dropped out of the competition for 5GTF and as a result they have not been investing in the higher power units at 28 GHz for the past six months or more.

Huawei reports EIRP of +65 dBm at 28 GHz, but we have not been able to confirm this number, or understand whether this figure represents the average RF power or the peak power.

Vendor	Band	Antenna Configuration	RF Power (average EIRP)	Size
Huawei	28 GHz	64T64R	+65 dBm (?)	Estimated 300 x 180 x 90 mm
Nokia	28 GHz	Unknown	+51 dBm	Estimated 200 x 180 x 80 mm
Ericsson	28 GHz	128T128R	+56 dBm	Estimated 180 x 180 x 80 mm without baseband Estimated 380 x 180 x 80 mm with baseband
Samsung	28 GHz	256T256R for each stream, 4 streams	+56 dBm	Estimated 380 x 180 x 80 mm

Figure 18. Comparison of various RRH/AAS products at 28 GHz

Source: Various vendors and Mobile Experts estimates

Network Slicing

The 5G network is expected to handle multiple applications with very different requirements:

1. Faster, cheaper broadband data;
2. Ultra-reliable, low latency IoT connections;
3. Massive IoT connections.

These three objectives drive very different requirements in the radio (IoT needs low frequencies for long range propagation, while broadband use requires high frequencies for wide bandwidth). At a radio level, we don't expect Network Slicing to be able to help at all.

However, at an overall system level, these different applications drive distinctly different usage of core network and baseband processing resources. The IoT applications don't need much supporting baseband processing in the data center (just the authentication and control signaling), so these functions can be supported inexpensively in the radio unit itself or at any stage along the way.

In the case of ultra-reliable low latency applications (these are the ones that will justify the use of 5G), we're likely to see functions such as user plane processing and even control plane processing moved as close to the user as possible. The time required for signals to travel 100 miles over fiber can be significant in these applications, so the central data center could be reduced to nothing more than billing and authentication functions.

The concept of "Network Slicing" allows the lighter applications such as IoT to bypass the hardware found along this chain. Where broadband mobile data needs to run through certain steps for mobility/handovers, or packet inspection, or compression, the IoT data does not need to be passed through those processing steps. Previous generations would have specified a single path for all data, but 5G Network Slicing allows the data to bypass unnecessary steps.

In a lightly loaded 5G network this feature may not have much impact. But when 5G networks are heavily loaded in the future, the concept of creating a slice for specific applications could improve the reliability or the cost profile for specific network applications.

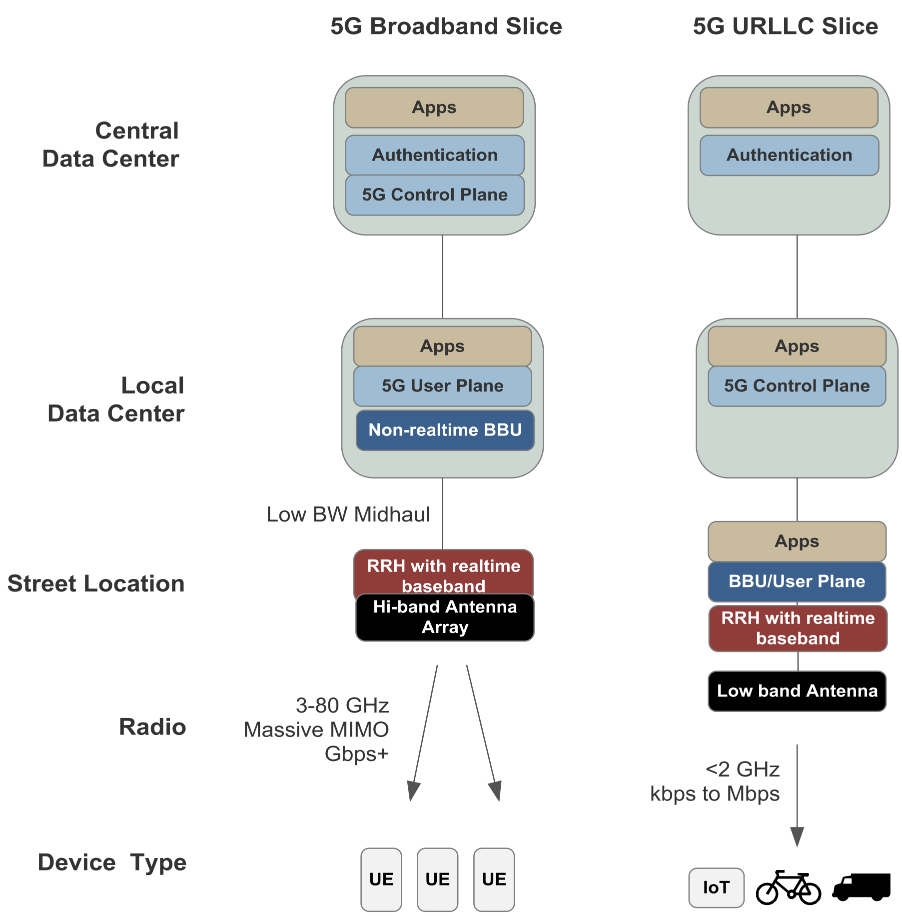

Figure 19. Possible 5G Network Slices for Broadband and IoT slices

Source: Mobile Experts

Essential elements of the overall 5G network include:

- A virtualized packet core. Separating the control plane and the user plane through the EPC is an important part of setting up network slicing. At the same time, the core network must be migrated to standard servers to bring the cost down for dedicated hardware.

- Local data centers will add more functionality, with some applications and user plane core network functions moving from the central data center to provide lower latency.
- The baseband processing will be re-partitioned so that the high-bandwidth requirements of CPRI will not extend to the 5G Broadband case. Realtime functions in the PHY and the lower MAC will be physically performed in the remote radio head, while non-realtime baseband processing (upper Layer 2 and Layer 3) will remain in the local data center for most broadband applications.
- The Remote Radio Head will take on PHY/MAC, and will be integrated with the antenna array for frequency bands above about 3 GHz so that Massive MIMO can be achieved without electrical losses between the RRH and the antennas.
- The IoT slices of the 5G network may use very different partitioning, with low-latency applications requiring applications, core network and baseband functions to be moved closer to the user.
- Note that the IoT applications are most likely to run at frequencies below 2.7 GHz, so the Integration Antenna Radio concept is not likely to apply. On the radio hardware, "network slicing" does not help because the radio hardware will look very different for the broadband and IoT slices. In fact, for some cases existing GSM or LTE antennas and radios may be utilized for 5G IoT.

Cloud RAN implementation

"Cloud RAN" is a vague term that, honestly, has lost its meaning in the industry, where so many vendors are using this terminology to mean different things. We break down the steps toward "Cloud RAN" as follows:

1. Centralization of the network: The use of RRH units in the field and baseband processing in a centralized data center can save money and allow resources to be shifted around. The physical co-location of BBUs in a data center is often called "Centralized RAN".
2. Virtualization of the core network: 5G core networks are expected to be realized as software running on a generic computing platform, so that a super-efficient cloud computing company (such as Amazon) would physically host the core network on its servers. This allows the core network to scale up easily and takes significant cost out of the equipment.
3. Hybrid RAN (Virtualization of some RAN steps): Baseband processing is more difficult than core networks to virtualize in some ways, because real-time processing of baseband signals can be required. Most OEMs are looking at ways to run upper Layer 2 and Layer 3 software on generic servers, with the remaining Layer 1/Layer 2 processing done in the radio head in real time. This kind of partial RAN virtualization will be a common first step.
4. Full virtualization of the RAN may happen in the future. We have seen demonstrations from companies like ASOCs that prove the feasibility of this approach, but the tradeoffs in a large scale network are not well understood yet.

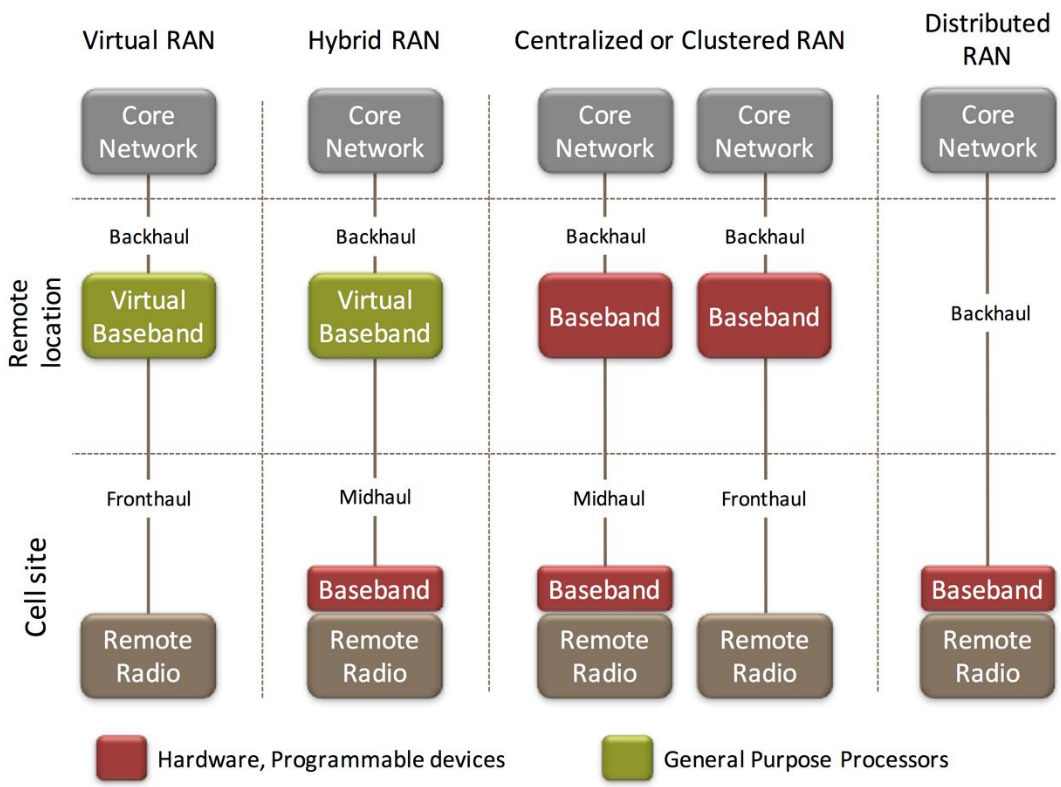

Figure 20. The evolution from Distributed RAN to Centralized RAN, Hybrid RAN and Virtualized RAN

Source: Mobile Experts

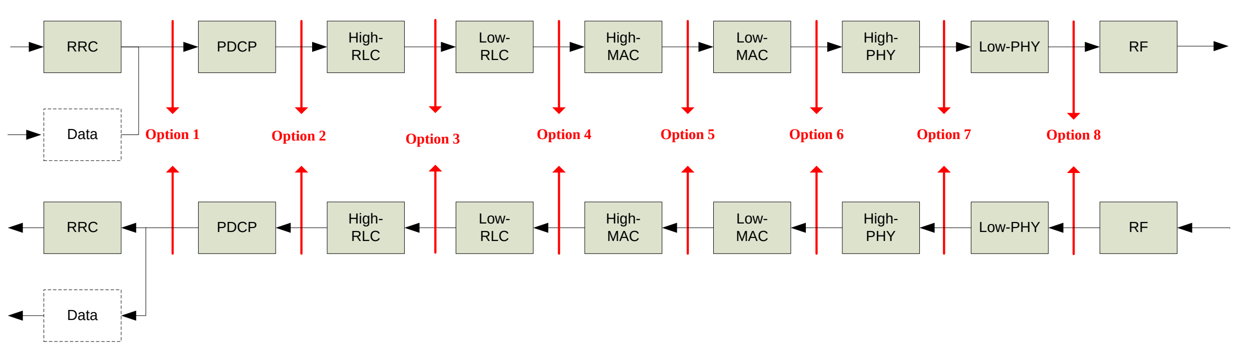

Figure 21. The possible baseband processing splits specified in 3GPP options

Source: Mobile Experts

Mobile Edge Computing Implementation

Mobile Edge computing can be viewed as simply placing cloud computing resources closer to the user, for improved services in local applications. Examples of interesting applications include facial recognition in airports, license plate readers at a toll booth, or gunshot detection from every streetlight in a city. These applications would benefit from having computing platforms available, as close as possible to the action, to perform the necessary application processing.

The obvious drawback of Mobile Edge Computing is the cost. Do the benefits of quicker service for the application outweigh the costs of adding computing cores at a local site?

We believe that MEC will be implemented in stages. Very few applications could justify the addition of a computing platform at the RAN site. However, at an IP-aggregation site the cost can be much lower. For example, in a big American LTE network today the mobile operator has ten IP-aggregation sites nationwide, supporting about 150,000 radio sites. Clearly, operating the computing platform at ten data centers is cheaper than adding computing platforms at all 150,000 radio locations.

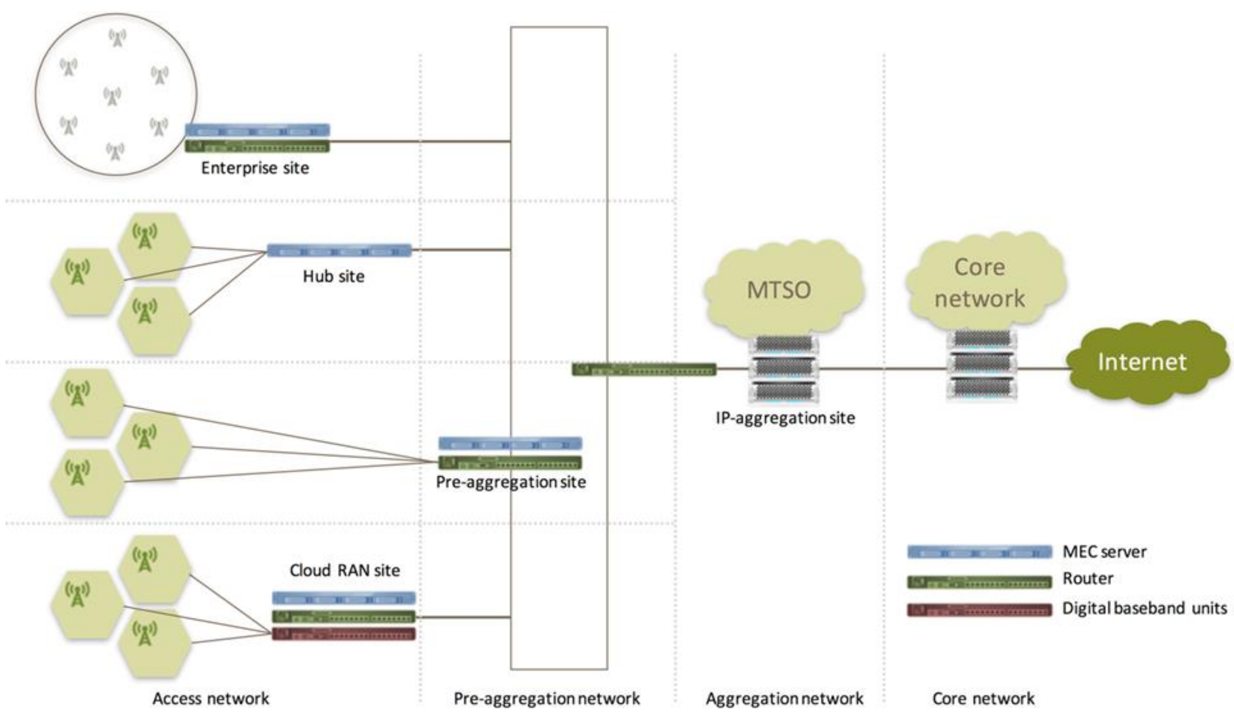

Figure 22. Overall 5G system architecture with Mobile Edge Computing

Source: XONA Partners/Mobile Experts

During the 5G deployment phase, a critical question centers on whether computing platforms should be built into the radio access sites. We believe that the level of resources applied at the radio sites will be minimal. Instead, pre-aggregation sites are more likely to be established in each city, so that our American network example would have hundreds of local data centers supporting MEC applications. This is a reasonable step from the ten IP-aggregation data centers they use nationwide.

Synchronization for 5G

As we coordinate radios more closely, the synchronization requirements keep getting tighter. To be clear, the 5G waveform itself does not drive any tighter synchronization requirements, but the use of Carrier Aggregation, adjacent-band CA, and Distributed MIMO are clear drivers for tighter precision. Also, some of the applications that run on top of 5G may drive tighter absolute time references in order to locate devices more precisely, or improve on ultra-reliable communications.

As things stand today, many LTE networks have already been upgraded to a relative time accuracy in the range of 40-50 nanoseconds, to support Carrier Aggregation features as laid out in 3GPP Release 13. (TS 36.104 section 6.5.3.1 defines relative time accuracy requirements and TS36.133 section 7.4 specifies absolute time between BBUs).

Sync Category	Application	Absolute Time accuracy	Relative Time accuracy	Comments
--	Coordination between two BBUs	3 microsec	--	Needed for handovers between base stations
B	Inter-band Carrier Aggregation	3 microsec	110 ns	Needed to stitch CA together
A	Contiguous-channel CA	3 microsec	45 ns	Needed to stitch CA together
A+	Distributed MIMO	3 microsec	10 ns	Needed to combine RF reception from different base station locations
--	Precision location	50 ns		Need to use multiple GNSS signals (L1, L2, L5)

Figure 23. Tighter sync requirements for applications on 5G networks

Source: Viavi, 3GPP, Mobile Experts

To reach these tight levels of timing precision, the network generally uses GPS as an absolute reference and IEEE1588 (PTP) to coordinate between sites at tighter levels. If new applications enabled by 5G latency or bandwidth require absolute timing that is tighter than 3 microseconds, then additional GPS or GNSS receivers can be added, increasing the cost and complexity on each radio site.

Inter-operator Synchronization

Two competing operators with TDD networks in adjacent bands will have problems without working together to synchronize the networks. According to Huawei, any two TDD networks in the 3-5 GHz range that are not synchronized will need about 25 MHz guardband to ensure proper operation. This is totally unacceptable, as the operators will only have about 100 MHz to work with, and they'd like to use a 100 MHz channel.

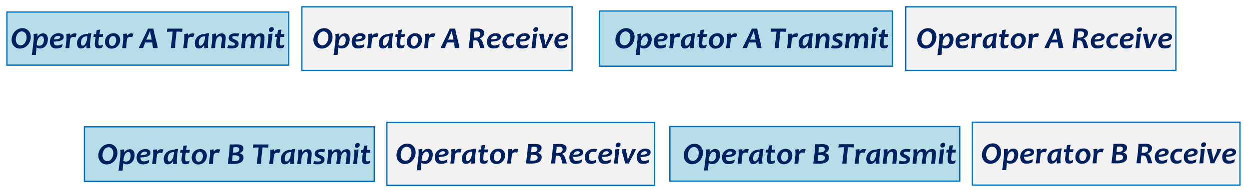

Figure 24. Illustration of problems with inter-operator synchronization

Source: Mobile Experts

This problem has come up before, and fortunately the timing precision does not have to be extreme. NTT DoCoMo, KDDI, and Softbank have solved this problem in Japan with their TD-LTE networks at 3.5 GHz. The absolute timing precision specified in Release 13 is good enough for this purpose… but the operators still need to coordinate in order to designate an uplink/downlink timing schedule, and they all must set the same uplink/downlink ratio.

This issue may not have major strategic importance, but it will require the operators to coordinate and work together. In some markets such as the USA the operators don't play nicely together so this issue could cause trouble.

Figure 25. Layout of Japanese TD-LTE with adjacent bands

Source: Mobile Experts

6 RADIO IMPLEMENTATION--INFRASTRUCTURE

Over the past three years, our coverage of 5G RF implementation has become more specific and we can now point to specific products that are coming into play. Major problems associated with power consumption/heat and EVM errors have been solved, at least for the first round of deployment.

RRH Implementation at 3-5 GHz--TDD

Because deployment of 5G NR in China is coming very quickly in late 2018 to 2019, the network OEMs have been scrambling to put together RAN products that work.

Most 5G base stations below 5 GHz will use an 8T8R configuration….not Massive MIMO. Looking at the cumulative forecasted shipments of 5G equipment over the next five years, we expect to see a lot of trials and early activity at 64T, but the massive nationwide deployment in China will include many rural base stations using an 8T8R configuration. We're also likely to see about 1/3 of deployment at 16T16R, with horizontal beamsteering but little to no vertical beamsteering. This breakdown is not at all certain, but is based on the expected capacity need.

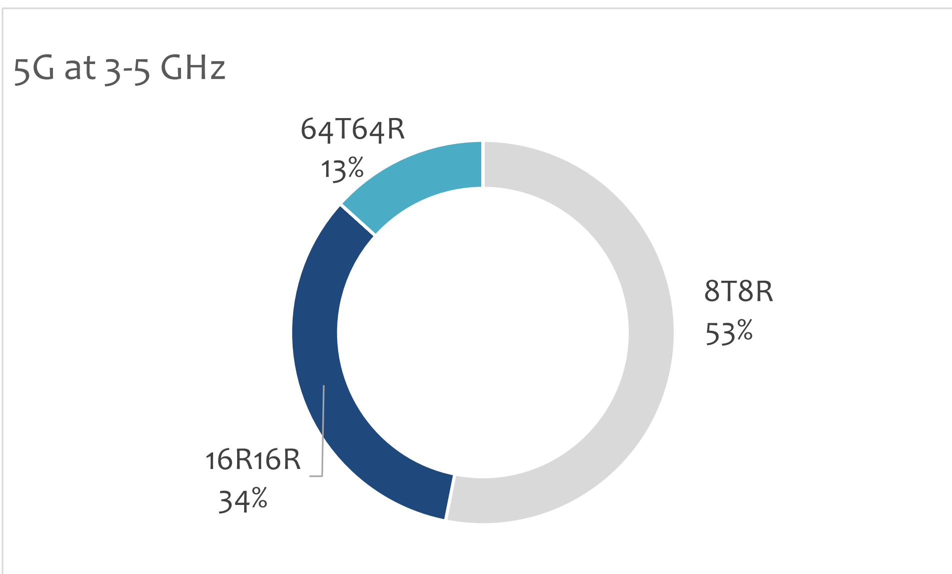

Chart 3: Breakdown of cumulative sub 6 GHz 5G NR RRH configurations, 2017-2023

Source: Mobile Experts

In urban sites, the 64T64R configuration will be reasonable and justified by the level of traffic. For example, over the next five years in Tokyo, Seoul, and Beijing, the level of traffic density in the network will rise to levels greater than 0.1 Gbps/km2/MHz. In these cases the high spectral efficiency and high capacity of a 64T radio will be worthwhile, and all major urban deployment in these TDD bands will be likely to use a 64T configuration.

However, the 5G network deployment in China will also include huge numbers of suburban and rural sites which do not require high traffic density. In these cases, the large size and high cost of a 64T antenna would not be justified, and an 8T8R configuration is much more practical.

8T8R. Standard configuration

64T64R. Integrated Antenna Radio configuration

Figure 26. Mechanical/integration shift toward Integrated Antenna Radios

Source: Mobile Experts/Ericsson

The practical issues related to Massive MIMO in the 3-5 GHz bands are now taken care of in very specific ways, and the major barriers appear to be solved for commercial roll-out:

1. The number of cables and connectors would be a problem for any sector above 8T8R. The sheer size of the connectors would force a change in the size/shape of the antenna because 8 connectors already consume the entire bottom surface of a typical antenna. Instead, from 16T to 512T systems the OEMs are introducing fully integrated antenna/radio products.
2. Adding a Massive MIMO antenna at 3-4 GHz without changing the existing 1-3 GHz antennas means that each tower must accommodate three additional antennas (one in each sector). This gets quite expensive, especially for leased space on towers. Therefore the OEMs have introduced active antenna systems with integrated passive antenna bands.
3. Large size antennas are challenging in terms of weight and wind forces. Without paying attention to this issue, a straightforward Massive MIMO design could easily result in an antenna width that's double the existing standard for tower mounting. To keep the wind loading down, the OEMs have changed the antenna spacings to allow for the Massive MIMO arrays (at 3-5 GHz) to fit into a normal 30 cm antenna width.

In all bands below 6 GHz, we expect full digital beamforming to be used, because the bandwidth of lower spectrum channels should be in the range of 5 MHz to 200 MHz. Full digital beamforming is quite possible for this bandwidth, without consuming too much power in computing. This means that all of the phase and amplitude shifts are calculated for the antenna elements, and no analog phase shifters or step attenuators are needed for the beamforming itself.

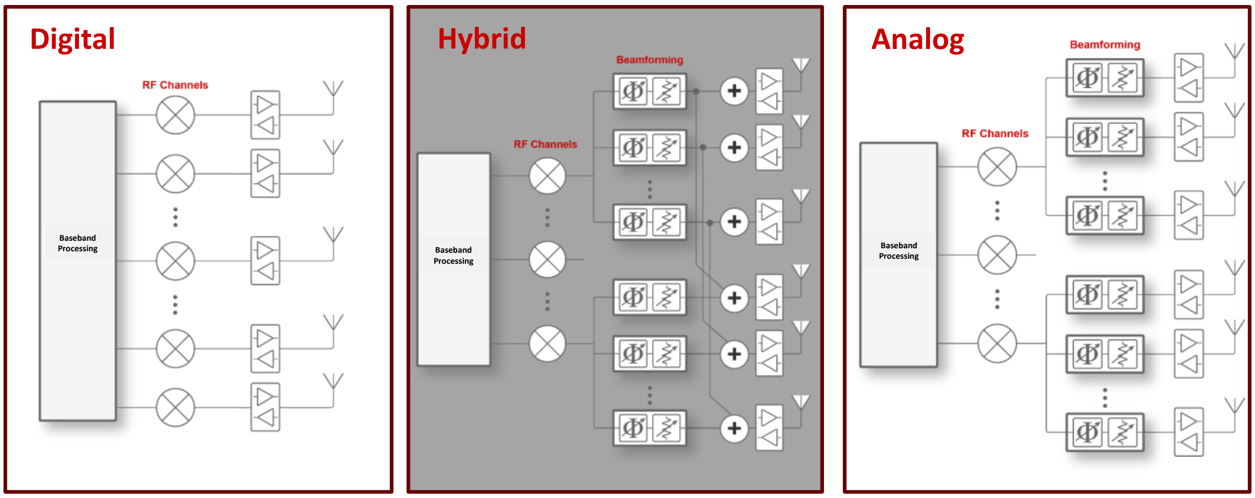

Figure 27. Block Diagrams for Analog, Digital, and Hybrid Beamforming

Source: pSemi

Uplink/Downlink imbalance—how to fix it

In 5G trials so far, the gap between uplink and downlink link budgets can be as much as 13.7 dB at 3.5 GHz. This means that coverage for a C-band network will suffer…the network needs a bi-directional link to operate effectively. Even if applications are expected to be downlink-heavy, the link budget gap needs to be narrowed.

Both ZTE and Huawei have demonstrated techniques to decouple the uplink and downlink, so that the higher band (3.5 GHz or others) can be used for the downlink, while a lower band (e.g. 900 MHz) can be used for the uplink.

Huawei has demonstrated this decoupled operation decisively in Gangnam, Seoul, Korea, as well as London, UK. In these trials, Huawei demonstrated a 70% coverage improvement in terms of the area in which uplink handles at least 5 Mbps.

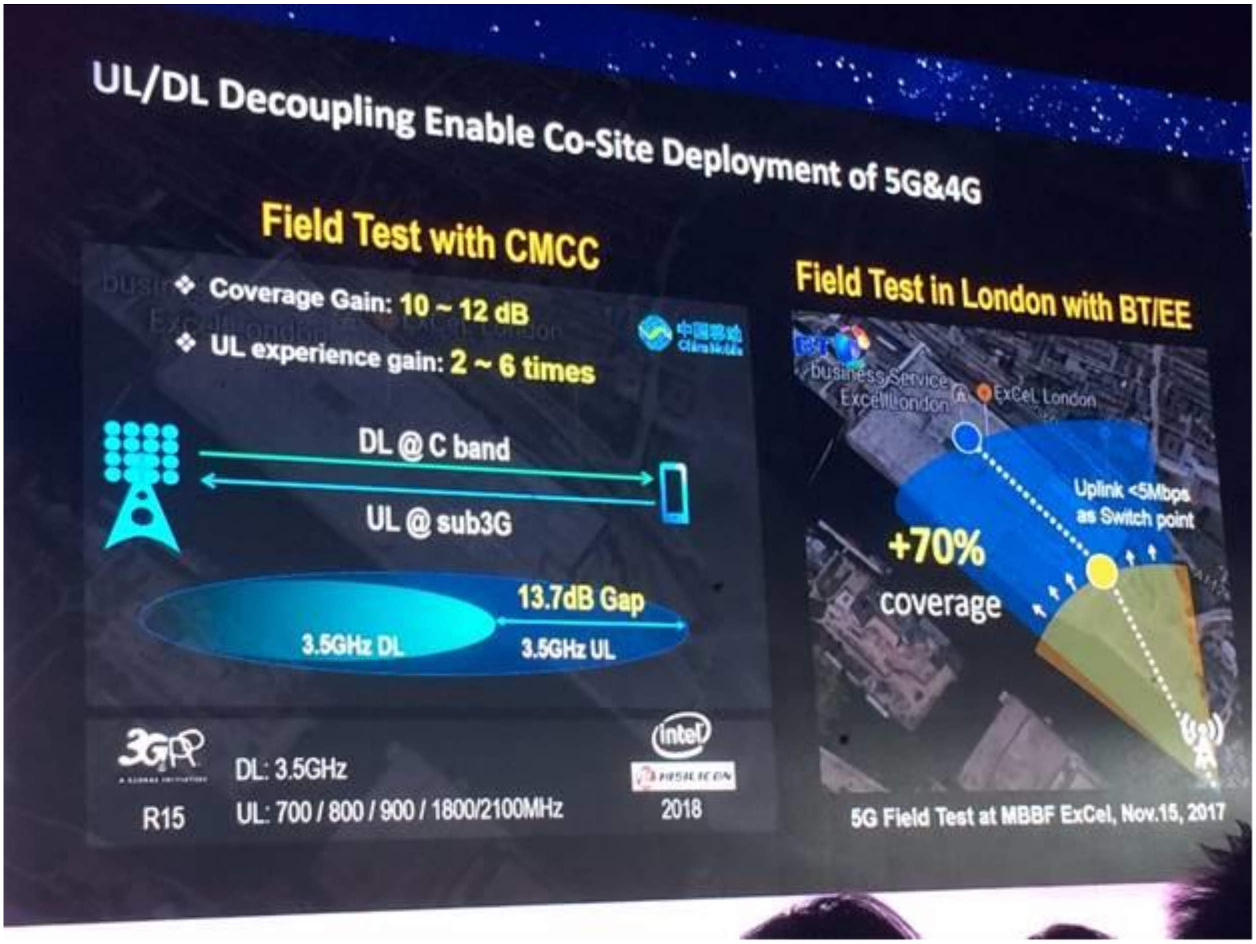

Figure 28. Uplink/Downlink decoupling helps the uplink by 2-6 times

Source: Huawei/MWC2018

RRH Implementation at 20-40 GHz--TDD

The RF components used at 28 GHz are very different than the approach taken in the 3-4 GHz range. Transitions and microstrip traces on a PCB are not going to work in the mm-wave range. For that reason, we expect to see much higher levels of integration.

In last year's report, we provided about 18 pages of analysis showing how GaN devices are likely to be used for mm-wave infrastructure, with hybrid beamforming and a highly integrated antenna/radio module. Instead of re-hashing all of that information, we offer the following abbreviated summary of our findings:

Physical Integration

The mm-wave radio will be highly integrated, with very close proximity for the antenna elements, filters, amplifiers, and data converters. In our view, the patch antenna elements that are most likely in the 28-40 GHz range must sit directly on top of buried waveguide filters and directly above the power amplifier/LNA components. Scaling this up to 256 elements or more will require a wafer-scale assembly or at minimum a set of multi-element components that fit together tightly.

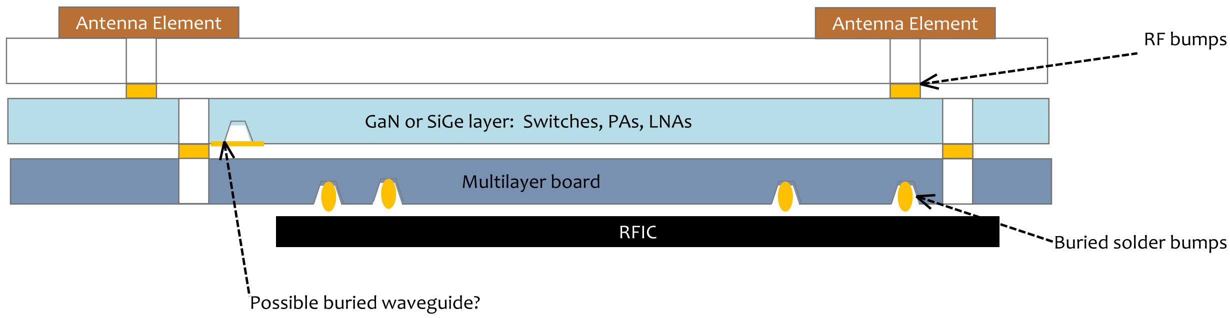

Figure 29. Possible construction of a high-power wafer scale assembly above 28 GHz

Source: Mobile Experts

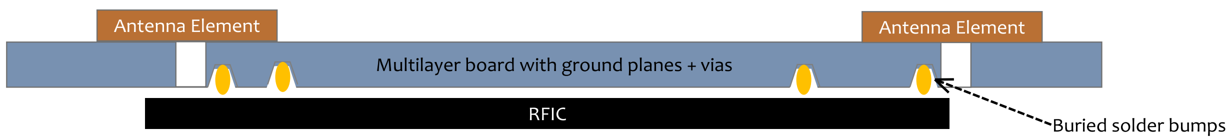

Figure 30. Simpler construction for a silicon 5G radio/antenna array

Source: Mobile Experts

One low-cost, low-loss way to integrate the RF array involves the use of low temperature co-fired ceramic materials (LTCC). Companies that manufacture LTCC RF modules for smartphones and other high-volume applications have brought cost down to low levels, and this approach allows for low-loss vias to connect RFICs with the antenna elements directly, with the potential for control over parasitic inductance/capacitance to achieve some rudimentary filtering.

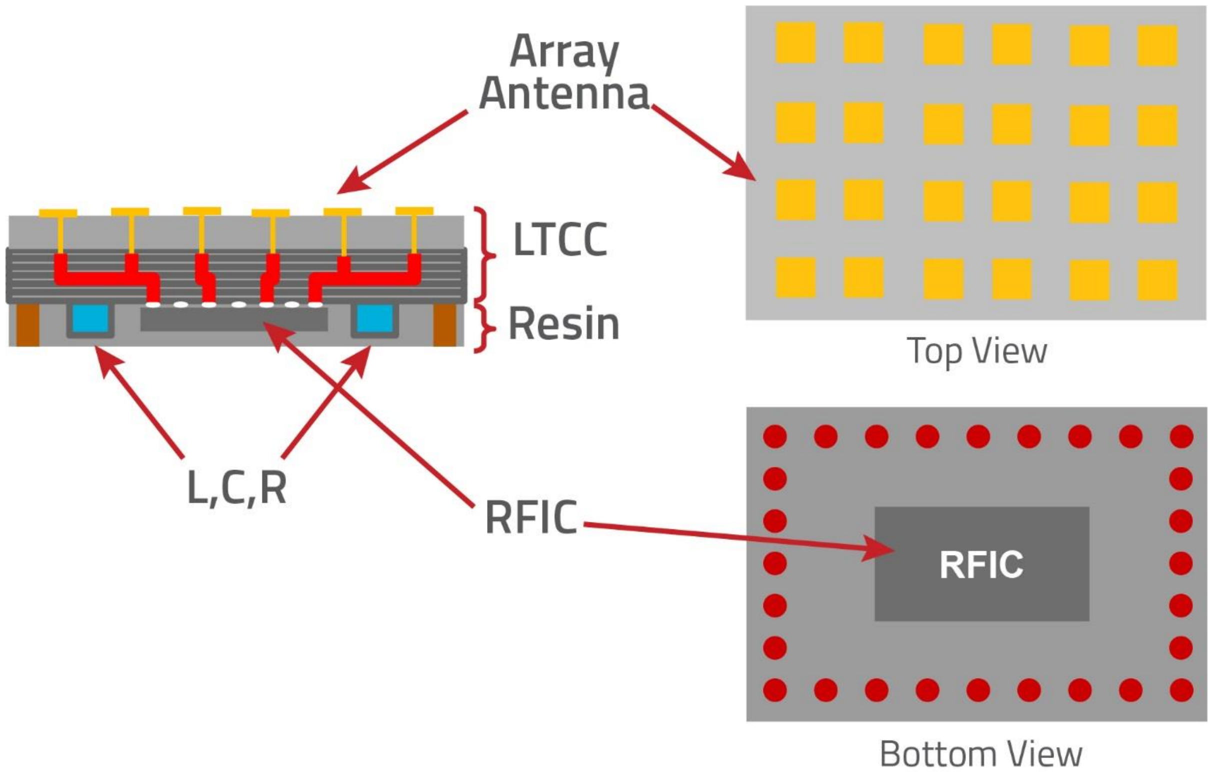

Figure 31. LTCC construction of an antenna array with RFICs and embedded passive devices

Source: pSemi

RF Semiconductor Process

The industry has not fully settled this question yet, but we are starting to see where silicon and GaN will fit in, for the RF front end of mm-wave radios. In an RRH, efficiency of the power amplifier is the #1 biggest factor in determining how much RF power can be achieved and how much heat will be generated. The efficiency performance, ALCR performance, and total EIRP will be higher for GaN, and silicon (SOI or SiGe) have lower cost.

It's important to note that the cost of the semiconductors themselves are a minor factor in the overall cost equation for mobile operators. Of course, semiconductor cost is important to the radio manufacturer, but the delta in cost from SOI to GaN is very small compared with the cost of additional sites due to short radio range.

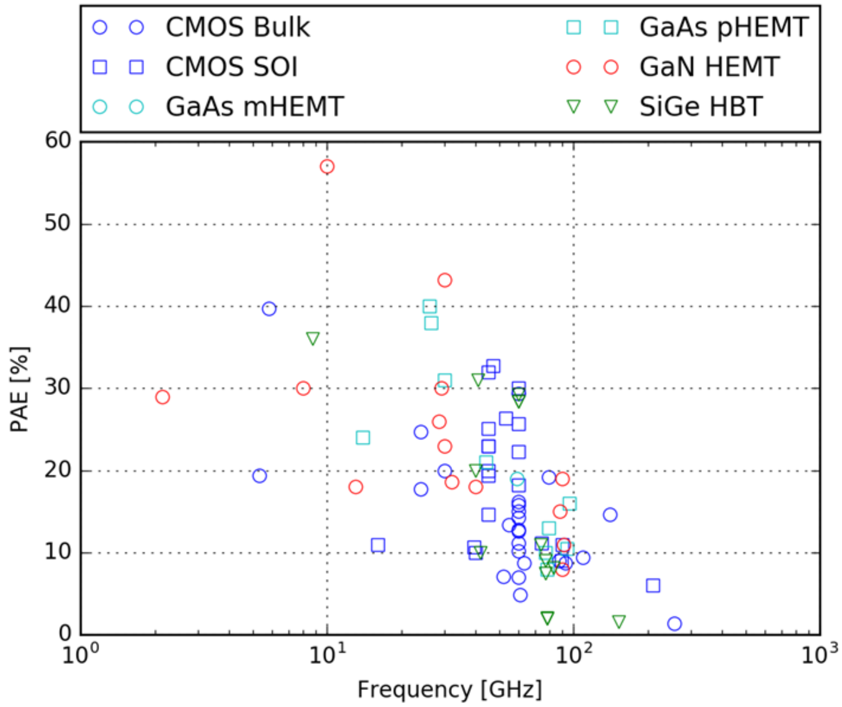

Figure 32. Comparison of CMOS, SiGe, GaAs, and GaN for mm-wave PA efficiency

Source: 3GPP RAN4

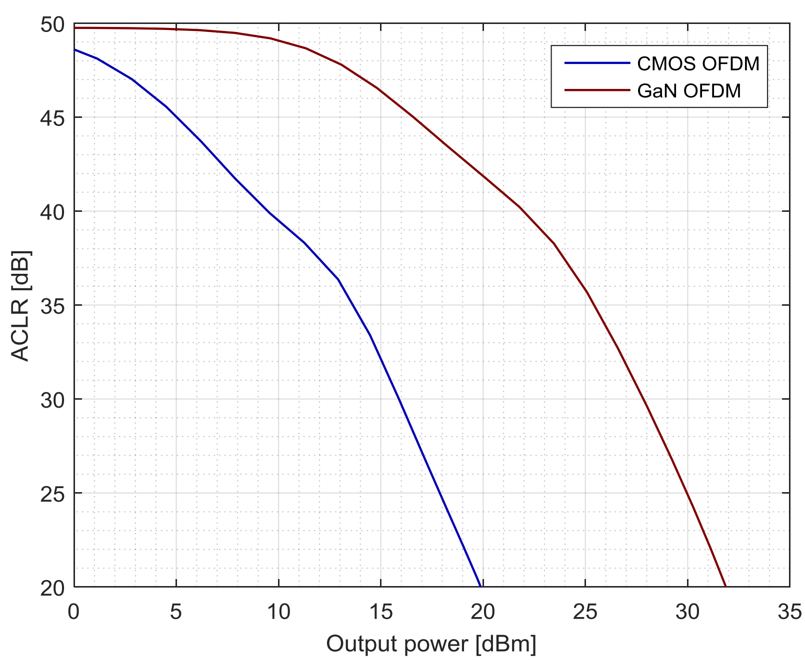

Figure 33. Comparison of GaN and SOI amplifiers for ACLR performance

Source: 3GPP RAN4

The two figures shown above summarize some of the key characteristics of GaN and SOI. Silicon can result in a cheaper, simpler module, but GaN has significant performance advantages in power capability, power-added efficiency, and linearity (ACLR) performance. GaN-based radios achieve roughly +65 dBm EIRP where SiGe and SOI-based radios achieve about +55 to +61 dBm EIRP, using more antenna elements. This is critical, as range is the single most important factor in the mobile operator's ROI equation. In the end, we expect to see SOI or SiGe in urban mm-wave sites, but GaN in suburban sites.

With GaN, the amplifier's efficiency and linearity are somewhat superior to silicon, so high EIRP can be achieved with fewer elements. The optimal point comes out about 120 elements at 28 GHz, in terms of achieving high EIRP with the lowest possible power dissipation.

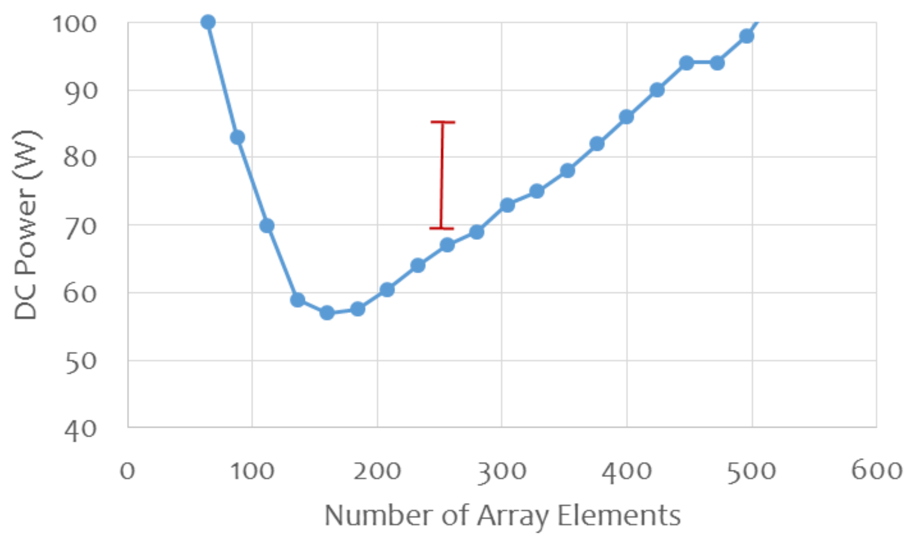

Figure 34. Amplifier power dissipation for +64 dBm EIRP at 28 GHz using GaN and SOI

Source: Qorvo/Mobile Experts. Assume 4% EVM.

The red bar indicates Mobile Experts' min. and max. estimates for power consumption using SOI

Silicon amplifiers have lower efficiency for the same linearity/EVM performance, but silicon is cheaper and larger arrays can make up for lack of raw power through antenna gain. Anokiwave showed the best-in-class array at MWC based on SOI, where they achieved roughly +60 dBm EIRP with a small 256-element array and a small heatsink. Based on the size of the heatsink, we estimate the power dissipation of the PAs to be roughly 35-50W for the entire array. This is possible because increasing numbers of elements adds antenna gain, so each amplifier must only provide about 7 mW of RF power to achieve 1000W (+60 dBm) EIRP. For SOI to achieve +64 dBm EIRP as demonstrated in GaN, at least double the number of antenna elements would be required, and we estimate that about 70-85W of DC power would be required.

Note that the extremely high antenna gain of a 512-element array (54 dB) reduces the power per SOI amplifier another step, but the power required to drive additional beamforming elements and beamforming calculations will become a factor. We believe that OEMs have chosen not to pursue silicon arrays above about 256T, because the complexity, cost, and total system power consumption become negative tradeoffs.

In the end, we see SOI as a great choice for EIRP below +60 dBm per stream. In urban applications for 28 GHz, this is probably enough power to reach outdoor users because of short urban inter-site spacings. However, for applications that need higher EIRP (penetrating buildings or suburban areas), GaN will be preferred to achieve +65 dBm or possibly higher.

Beamforming

Radio engineers would like to achieve the ultimate in digital beamforming, with the DSP processing cores setting phase and amplitude for each element digitally. That's possible for narrow bands below 6 GHz, but for a 1 GHz bandwidth in the mm-wave range it's not a good tradeoff currently. The main drawback of the pure-digital beamforming technique is related to power consumption, as the correction of wideband steering for a large array can be very computation-intensive.

Above 24 GHz when side bands and wide steering angles are required, the power consumption of a digital beamformer can be prohibitive, so the major OEMs have considered analog beamforming. The analog approach has been used in radar systems for more than 60 years, and works great for narrowband signals. Analog beamforming allows for narrow beams using a lot of elements, but it lacks the flexibility of a digital beamformer.

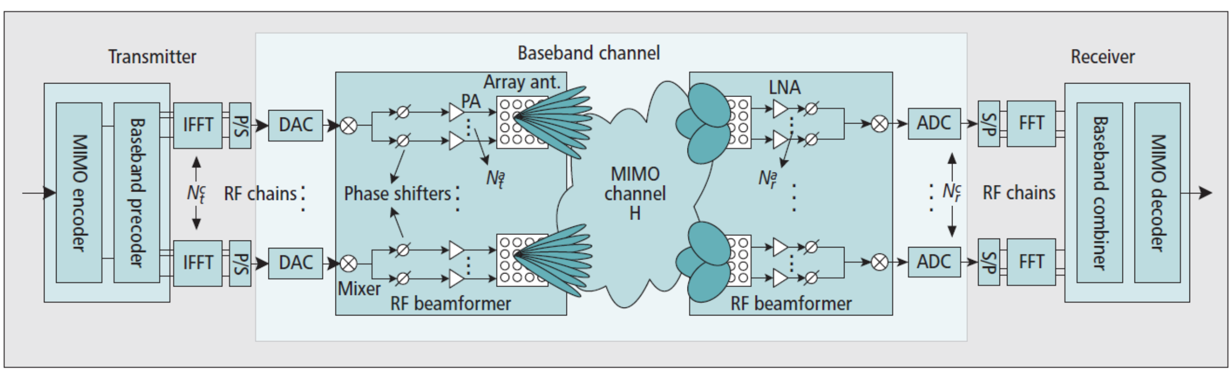

Figure 35. Hybrid Beamforming—end to end diagram

Source: Samsung

In particular, one issue with using a pure-analog approach is that analog beamforming only works well for narrowband signals. Wideband signals that are steered with simple analog phase shifters result in significant EVM errors, because the phase shift is only accurate for the center frequency, not the band edges.

To get the best combination of high gain (narrow beams) and the flexibility of digital processing, variations on the hybrid approach will be used by all major OEMs. In essence, the hybrid approach allows grouping of antenna elements to keep the number of RF paths to a minimum, while still allowing for a large number of elements and the corresponding narrow high-gain beam.

We expect hybrid beamforming to be used until Moore's Law can provide low-cost, low-power computing resources to handle very wide bands in a more practical way.

ACLR, Linearization, and related issues.

Now that 3GPP has settled down on CP-OFDM as a waveform for both uplink and downlink, we're starting to see the benefits and the issues related to it. Compared with other possible multiple access formats, the peak-to-average-power ratio (PAPR) of CP-OFDM is fairly high at about 10 dB. This will remain a little higher than LTE after accounting for crest factor reduction. Spectral efficiency is high, but the frame is contained so that it doesn't spread out in the time domain, making low latency possible. Out-of-band emissions are also high, but Qualcomm has proposed the use of WOLA (Windowing Overlap and Addition) to reduce out-of-band emissions, and we believe this technique will be used by manufacturers independent of the standards.

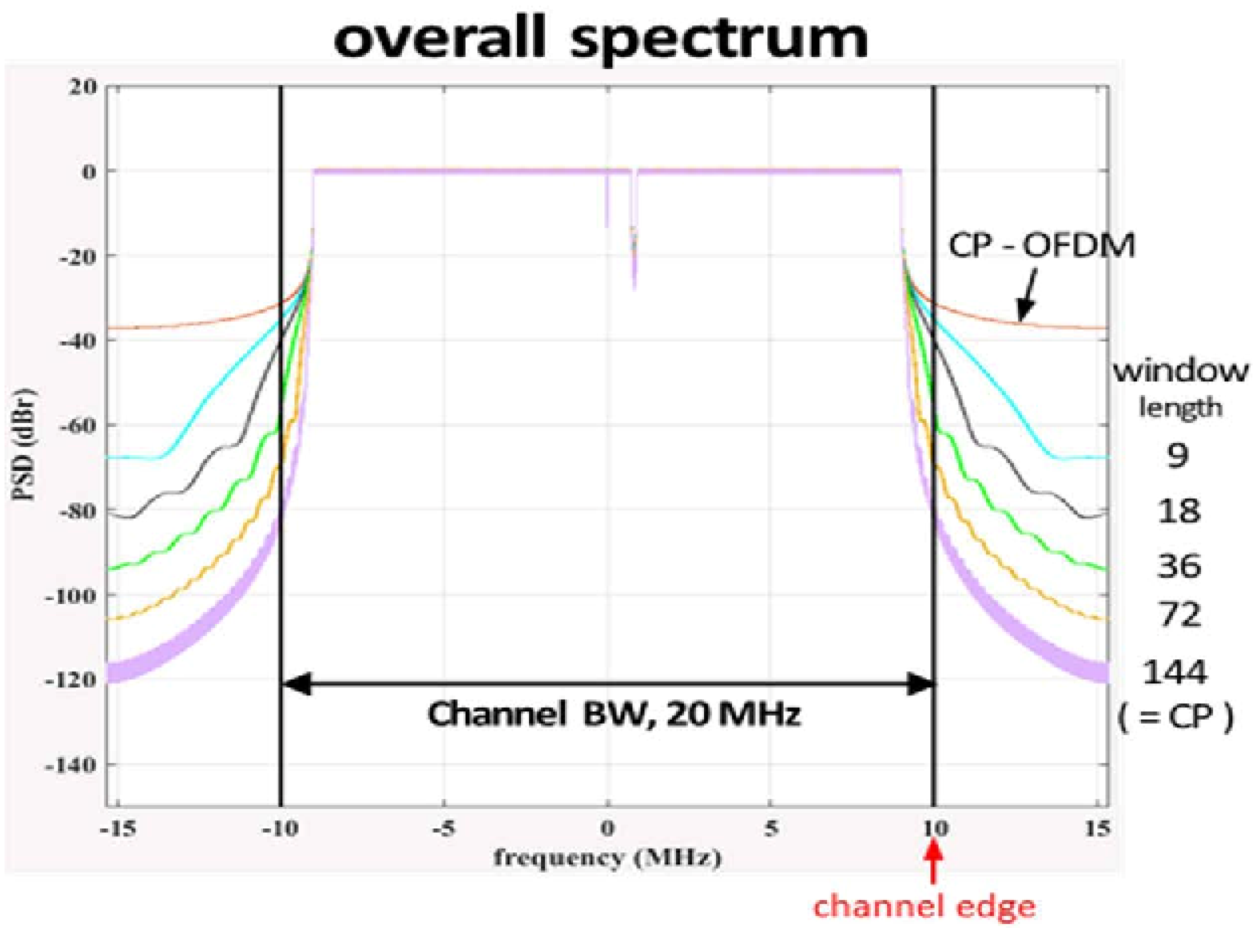

Figure 36. Out-of-band emissions for CP-OFDM with windowing

Source: Changyoung An et al, 2017 Ninth ICUFN

The ACLR specification for mm-wave systems has been set at 26- 28 dBc, substantially lower than the 45 dBc level required for LTE. The hard limit is still the same, at -13 dBm/MHz… however in the case of Massive MIMO systems we expect the relative specification (-28 dBc) to be the most relevant test. Note that -28 dBc applies to the 24-33 GHz band, while 37-53 GHz bands are relaxed to -26 dBc. This is fairly close to the prediction that we made two years ago, expecting the ACLR spec to be about -30 dBc. This decision was made between OEMs and operators as a way to ensure that silicon-based RF front ends would be possible…

Table 9.7.3.3-1: *BS type 2-O* ACLR limits

NR Channel bandwidth	BS adjacent channel centre frequency offset below the lower or above the upper Base Station RF bandwidth edge	Assumed adjacent channel carrier	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit [dB]
[50, 100, 200, 400, …]	$BW_{Channel}$	NR of same BW	NR of same BW with SCS that provides largest transmission bandwidth configuration (BW_{Config})	28 (Note 1) 26 (Note 2)
NOTE 1: Applicable to bands defined within the frequency spectrum range of 24.24 – 33.4 GHz NOTE 2: Applicable to bands defined within the frequency spectrum range of 37 – 52.6 GHz				

Figure 37. ACLR specifications for 5G NR in mm-wave bands

Source: 3GPP

Filters

All of the OEMs that we surveyed are planning to use simple low-loss filters in the 3-6 GHz band, but no specific filtering component in the mm-wave bands. Because the ACLR specs have been set to be pretty light, a filter is not necessary to control out-of-band emissions. Also, in the mm-wave bands, directional signals from radar, satellite, and other interfering sources will be unlikely to directly impact the receiver. Almost everybody is depending on the use of directional antennas to make the filter obsolete in these bands.

Having said that, at the RF module level the engineers will use clever techniques to enhance the resonant "filter-like" properties of the antenna and transmission line. At 28 to 39 GHz, the antenna patch will have a resonance at a given frequency, and the RF signal will travel through a via to the backside of a dielectric material. (see our RF implementation section for some diagrams). In this way, clever engineers will be able to protect the receiver with 10-20 dB of rejection of unwanted signals that are not in directly adjacent bands.

2-6 GHz 5G Network Architecture

For the major 5G opportunities in the 3-5 GHz band, we expect to see roughly half of the market use 8T8R radios, while the other half of the market will utilize a mix of 16T16R through 64T64R radios. The distribution of the massive MIMO arrays will take place in areas where the traffic demand calls for higher spectral efficiency… essentially, in urban sites and near train stations where 5G can be utilized.

Dual-band 8T8R radios

The rural application of 5G in China will use the existing LTE towers and the goal is to deploy 5G without making structural upgrades to the tower itself. This means that the existing 8T8R radio for TD-LTE (in the CMCC case) needs to be upgraded for dual-band operation.

Huawei has demonstrated this product already, and Nokia also has an innovative solution to the dual-band requirement. So, the concerns about half-wavelength spacing of antenna elements are being solved by each company using different means, and we expect that most of the China Mobile sites will be deployed as dual-band 8T8R antenna units.

In this type of radio configuration with 16 transceivers, it's impractical to continue the practice of using jumper cables between the radio and the antenna unit. We expect this round of deployment to move to integrated antenna/radios, so that both 2.5 GHz and 5G radios will be integrated in the antenna enclosure.

Figure 38.   Legacy approach to 8T8R radios

Source: s4gru.com

Figure 39. Integrated antenna/radio approach to 64T64R

Source: Huawei

To support the dual-band requirement, we expect a total composite RF output power of roughly 200W or more, which means that the efficiency of the power amplifiers will be critical.

Semiconductor integration for RF Front Ends in Massive MIMO, 3-5 GHz

One direction of this development effort involves the use of "Front End Modules" which incorporate the power amplifier, switch, and LNA for each antenna element. The sheer number of antenna elements in a 2.5 GHz or 3.5 GHz antenna array means that tight packaging and low cost are high priorities… and several major OEMs are moving toward integration of these devices in a multi-chip module.

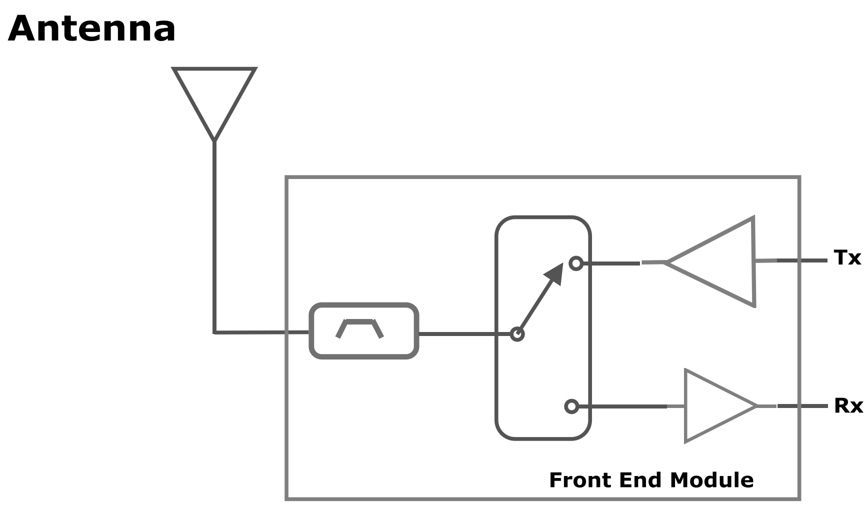

Figure 40. Block Diagram for a 3-6 GHz RF Front End Module

Source: Mobile Experts

GaN vs. Silicon for 3-5 GHz Massive MIMO RF Power Amplifiers

Most companies plan to use GaN technology for power amplifiers in the 3-5 GHz band, and in particular Huawei is promising a 200W composite power from a 64T unit (over 3W per output), which we believe is only possible using GaN. (It could be possible with silicon using fans to cool the RRH, but we don't believe that anybody will buy an actively cooled RRH for mobile telecom).

However, for a single-band 64T64R array, we've seen demonstrations that SOI can do the job with a high level of integration and about 2W per antenna element. Nokia has an impressive demonstration of a system at 120W RF output power (64T64R) which fits into a small, passively cooled enclosure. For urban applications, 120W should be enough….so the GaN vs. silicon battle will continue through at least the next year.

One issue is not related to technology as much as the practical side of producing high volume components. Some vendors have raised a concern that GaN on Silicon Carbide is produced on 200mm wafers, which means that a spike in volume for Chinese Massive MIMO radios would exceed the ability of GaN foundries to supply enough parts. GaN suppliers are working with Huawei and others this year to establish ramp-up plans. One possible solution is to move to GaN on Silicon, which can be scaled up to 300mm or 400mm wafers (6" to 8"), producing higher numbers of devices. Because 5G amplifiers in Massive MIMO will output only a few watts, this approach may be very sensible to scale up production.

7 RADIO IMPLEMENTATION—USER EQUIPMENT

Client devices for 5G will include handsets, tablets, PCs, mobile hotspots, and IoT devices. The scope of this report focuses on broadband client devices, so any low-bandwidth IoT applications that convert to 5G are not covered here. The big challenges for these devices will be similar to previous generations of phones: driving to low cost, low power consumption, and small, simple radios.

Fixed Broadband: CPE Implementation

The first commercial 5G networks will offer fixed wireless access to residential users, at 28 GHz and higher. The development of CPEs has advanced over the past two years, to higher complexity because the RF link budget for this service is challenged. Verizon and AT&T want to use CPE devices that are located indoors, near the user with easy set-up to avoid an expensive truck roll. However, these signals do not penetrate buildings well, so 10 dB or more must be added to the link budget to account for NLOS reflections, attenuation through walls or windows, and other factors. Some of the additional gain has been provided through higher power in the infrastructure, with higher gain antenna arrays and higher power amplifiers. 4x256T arrays (1024 elements total) is now

The CPE has also added significant link budget improvement through the use of higher order antenna sub-arrays on the CPE unit. Instead of the 8 antenna elements originally envisioned, recent CPEs have 32 antenna elements for at least 10 dB higher antenna gain. (Theoretical gain is 12 dB but we have not been able to confirm that 12 dB higher antenna gain was achieved).

With this combination of link budget improvements (adding 15 to 18 dB), Verizon's trials have been able to succeed with more than half of their CPEs located indoors, even with base stations located an average of 300 meters apart.

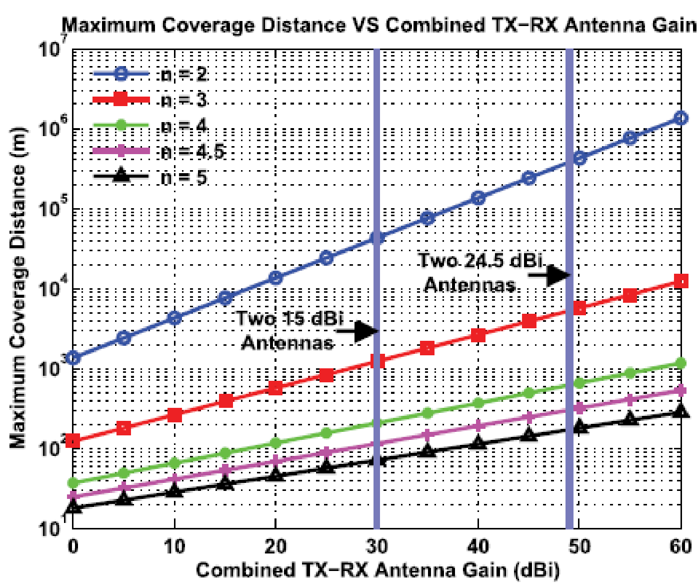

Figure 41. Modeling of RF link distance as a function of combined Tx/Rx antenna gain

Source: Professor Ted Rappaport, NYU

Mobile Broadband: 5G Handset Implementation

Over the past year, we have seen significant progress toward 5G radios in handsets. Qualcomm and Intel launched modems for 5G NR in November 2017, a month before the 3GPP standards were officially ratified. Huawei/HiSilicon released 5G modems in February 2018. Qualcomm has already announced design wins with handset OEMs for their 5G modem family.

Below 6 GHz, the implementation of a 5G handset will make smooth progress. Indeed, we already have handsets in Japan with radios in the 3.5 GHz band, and the modems are on the market. So how long will it take to put them together? Clearly the C-band handsets will be ready with 4x4 MIMO when the networks are ready.

One interesting twist below 6 GHz is that China Mobile has declared uplink MIMO to be "essential" for 5G NR. At 3.5 or 4.9 GHz, we can expect China Mobile to require 2T4T configuration in all of their handsets, driving up the RF content in the handsets.

Above 20 GHz, the technology challenge is very different. Placement of the antennas will be critical, and power consumption could be a major issue for some applications. We have seen significant progress over the past year, causing us to increase our forecast for mm-wave adoption in handsets.

- Qualcomm has demonstrated operation of two 4T4R subarrays at 28 GHz in a handset form factor
- Qualcomm has also illustrated the expected coverage of a mobile 28 GHz network, using the same cell site locations currently used below 3 GHz. These simulations are encouraging, with 80-90% of outdoor locations available for a high-capacity channel in aggregation with LTE. (Indoor locations would clearly not work as well)
- Mediatek has also demonstrated a handset with two 8T8R subarrays at 28 GHz. No performance data are available for this one… but Mediatek's commitment to this R&D effort is an encouraging sign that handset OEMs perceive a market need.
- Multiple players have described innovative antenna concepts in which multiple sub-arrays on the handset can be synthesized into a steerable antenna, making use of whichever antenna elements have adequate channel conditions.

The most problematic consideration is the attenuation of the human hand on a 28+ GHz signal. Measurements by Samsung and others indicate that a human hand (or any similar-sized object with heavy water content) will attenuate a 28 GHz signal by 30-40 dB. This is enough to kill the 5G link.

To compensate, the handset OEM is likely to use antenna diversity. In other words, they will use multiple sub-arrays. In one such example, the handset would include a 28 GHz array, with subarrays on each end of the phone, so that even large hands cannot cover all antenna elements easily.

In the configuration shown by Qualcomm, eight antenna elements are arranged in a sub-array, and three or four sub-arrays are placed on various locations around the handset. The transmitted power level for each antenna element could be quite high, because the low expected gain from the antenna sub-arrays could result in a poor link budget in the uplink.

Figure 42. One possible implementation of three sub-arrays in a handset

Source: Qualcomm

A further challenge is the three-dimensional pattern requirement from the handset. People don't hold their handsets in an RF-friendly orientation all the time. This means that a mm-wave antenna array in the handset must include the ability to steer in three dimensions. We expect the steering and switching of multiple elements to become highly sophisticated in a smartphone application, because the hand will cover arbitrary elements while leaving other elements open. The algorithm will need to figure out how to optimize the antenna pattern with the antenna elements available.

The sub-array in a handset is unlikely to achieve high gain due to cost and space constraints, but academic papers released so far indicate that 6-10dBi is a reasonable estimate for handset array gain.

Antenna sub-arrays

Each antenna sub-array can provide a steerable pattern in two dimensions, but the handset is a three-dimensional challenge. That's why two arrays will be situated at each end of the handset, in order to achieve a pattern which is adaptive in all three dimensions.

This fairly straightforward exercise is complicated by the presence of the user's hand. At 1-2 GHz, the hand has an impact on the antenna pattern, reducing Total Radiated Power by 5-6 dB in some cases. However, at 5 GHz the impact could be more than 10 dB and at 28 GHz the impact could be a devastating 30 dB.

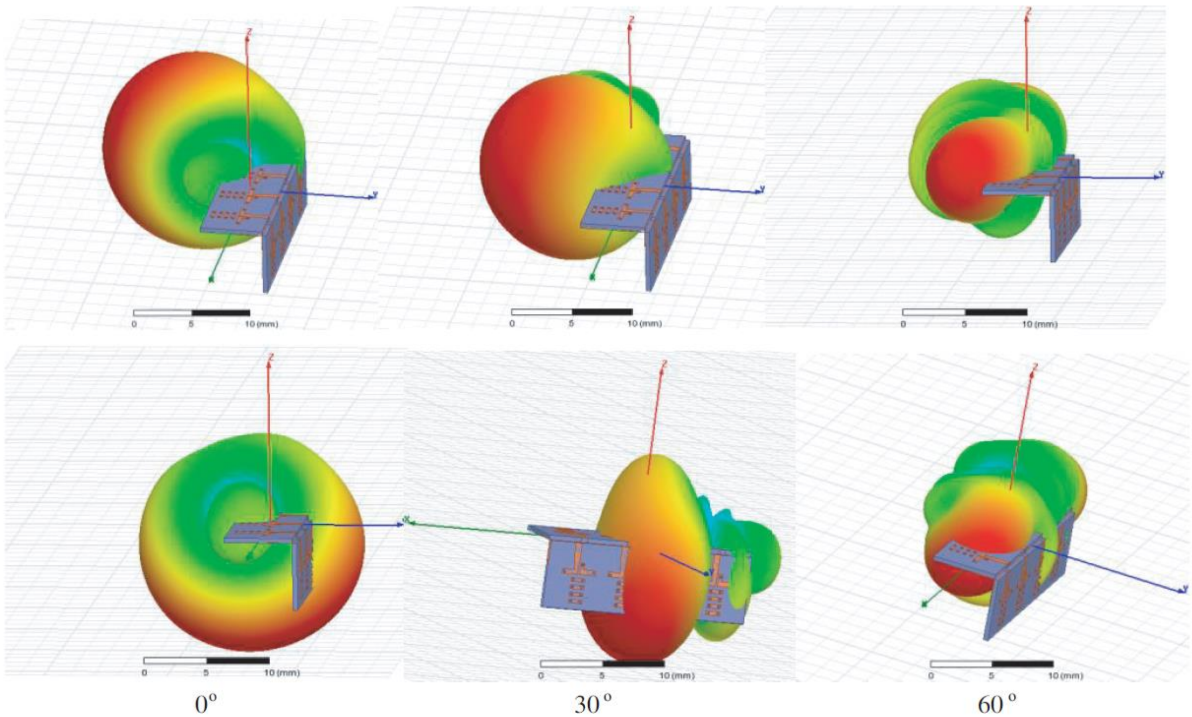

Figure 43. Various antenna patterns achieved with four 28 GHz antenna subarrays

Source: Shanghai University

To compensate for unpredictable hand placement by the user, the combination of antenna elements must be extremely flexible, allowing any combination of elements in the array to optimize the best possible beam pattern.

Semiconductor Considerations

The optimal choice of semiconductors for mobile mm-wave 5G is not clear yet. Most proponents of this application consider bulk CMOS to be the ideal choice, citing its use in WiGig at 60 GHz and other mm-wave products as proof of performance. We're not convinced yet, as we consider the challenge of the mobile uplink to be different than short-range WIGig and other solutions.

Linearity at high power is one prime consideration. Fortunately, the 3GPP committees set low ACLR requirements for transmitters above 24 GHz, so SOI/SiGe solutions should be adequate in the handset for ACLR. The EVM specification is more likely to dominate the design of the RF chain, but it's too early for us to have a good understanding of EVM's impact on the RF PA.

Overall, for cost reasons we expect that the only viable solution will be based on a large-wafer silicon process. A high degree of integration between the RF front end and the up/downconverters, as well as data converters, will be critical to building a radio economically. Using 24 or more discrete GaAs amplifiers along with a silicon RFIC may be too expensive to succeed in a handset.

Battery Life Impact of mm-wave 5G handsets

A millimeter-wave radio in the handset would consume higher power than a radio in the typical 1-2 GHz bands, due to poor propagation in higher frequencies, lower amplifier efficiency, and the processing needed for wideband, high-speed link. In this way, the viability of a mm-wave 5G handset will depend on the use case:

- Typical video download or streaming applications should be ok. In this case, the ratio of downlink to uplink can be at least 10:1. For this type of use case, the uplink would only transmit short bursts and the thermal and battery impact could be manageable. In downloading a video or another big file, the uplink requirement should be only for acknowledgement and operation less than 10% of the time.
- Two-way video applications such as "video chat" or VR gaming could be a problem. In a case where downlink-to-uplink ratio is 1:1, we can expect the mm-wave transmitter to operate in a continuous duty cycle. Notably, we don't currently have any applications which would drive a need for 100 Mbps or more in continuous symmetrical operation. Assume that the continuous stream would average about 20 Mbps (compared with HD video at less than 10 Mbps). In a practical sense, the 5G radio would operate at 200 Mbps, about 10% of the time to provide the user with a perceived 20 Mbps experience.

In TD-LTE networks today, the power from the uplink transmitter is already an issue, and we expect that the link balance will not improve as we move to higher frequencies.

This means that the Class 2 power levels of TD-LTE (HPUE) are a minimum level that will be necessary from the handset, at least in terms of equivalent EIRP. At 2.5 GHz, TD-LTE is moving toward high power operation in an attempt to balance the link budget, boosting the handset transmitter by about 3 dB to about +23 dBm. Given the efficiency of GaAs amplifiers at 2.5 GHz, at about 45%, this approach dumps about 1.5W of heat into the handset.

	RF Power level	DC Power Dissipation
Modem	--	---baseline case--
Transceiver	Low	--baseline case--
Power Amplifier	+27 dBm at output	1.1 Watts
Filters/Switches	+23 dBm to antenna	--
	TOTAL	1.53 Watts in operation
	50% duty cycle	**0.76 Watts average**

Figure 44. Handset DC power consumption for TD-LTE PA at 2.5 GHz—video chat case

Source: Mobile Experts

For now, we assume that at 28 GHz at least two transmitters will be active at the same time, to achieve some rudimentary steering. Power amplifier efficiency will be lower at 28 GHz due to the higher frequency, but the lighter ACLR requirement means that efficiency may not be as bad as previously anticipated.   We're estimating 35% efficiency for the 28 GHz PA.

	RF Power level	DC Power Dissipation
Modem	--	400 mW (extra for wider bandwidth for 5G NR)
Transceiver	Low	30 mW
Power Amplifier (x2)	+27 dBm at output	1.43 Watts (x2)
Filters/Switches	+23 dBm to antenna	--
	TOTAL	3.29 Watts in operation
	10% duty cycle	**0.33 Watts average**

Figure 45.   Handset DC power consumption for 5G NR PA at 28 GHz—video chat case

Source: Mobile Experts

These tables lead us to an interesting conclusion: 5G will actually save power in the battery, because for today's applications, 5G speeds are not necessary and the radio can turn off for 90% of the time. The issues will come if new applications (VR gaming??) drive the uplink to a 50% duty cycle, where 1.6W of extra heat will be hard to manage inside a smartphone.

8 COST ESTIMATES

The cost of a 5G network breaks into two major elements: Network cost is critical, including both the up-front capital investment and ongoing operations and maintenance costs. Also, handset or CPE costs must be reasonable, including the cost of the components inside as well as the practical costs related to installation or supporting the client devices.

Infrastructure—Cost per Mbps of raw capacity

The total cost of ownership for 5G infrastructure will come down to a few key factors. Below 6 GHz, we expect the RRH to share the same towers that operators have already established in the LTE network. So the big costs of siting, legal hassles, and trenching for fiber may be avoided in many 5G network deployments. The cost of the radio hardware itself could become a larger fraction of the total cost.

Despite the huge complexity of a 64T64R radio, We've been expecting reasonable cost for 5G RRH units, expecting that on-board baseband processing and complex radio configurations will add cost. Over the past year, we have seen some innovative solutions that should be delivered at lower cost than our original expectations. Good news for 5G deployment, as the positive ROI that we anticipated in 2017 looks even better this year.

There are a few major factors at work in estimating 5G costs:

1. **Massive MIMO configuration**. At least half of base stations deployed below 6 GHz will not use Massive MIMO….instead they will use either 4T4R or 8T8R radios, with a straightforward scaling-up in frequency compared with TD-LTE radios. This means that the cost of simple sub-6 GHz radios will be very similar to the TD-LTE deployment in China. On the other hand, Massive MIMO systems will require large numbers of radio components, beamforming devices, and processing for the beamforming calculations.
2. **Frequency band**. Below 6 GHz, existing discrete component techniques and PCBs will look very similar to LTE radios. In Massive MIMO cases, some vendors have innovative low-power RFICs using silicon instead of the more expensive GaN components. This is viable for the 64T64R level of complexity because the power transmitted by each amplifier will be lower than about 3W. In this way, major vendors are expecting to meet aggressively low cost targets.
3. **Open RAN standards**. Mobile operators are flexing their muscles recently, and we've seen signs that the operators may be able to force Nokia/Ericsson to adhere to an open standard between the BBU and the RRH. If this happens for 5G equipment, radio costs should come down by about 50%.
4. **Virtualization**. If the baseband processing can be virtualized in a data center, then avoiding special hardware for BBUs will also bring down the cost. We've had these savings baked into our model for the past three years. Virtualization, along with ongoing use of Moore's law, essentially drops the cost of baseband processing in terms of $/Gbps by a factor of ten or more compared with LTE.

5. **Backhaul**. For sub-6 GHz macro deployment of 5G, backhaul in many cases will only require the upgrade of fiberoptic transceivers, to make use of the existing fiber using DWDM techniques for higher capacity. This cost would be focused on the front end, with little impact on TCO. For 20+ GHz deployment of small cells, new backhaul must be put in place because the sites will be new.
6. **New Sites**. It's shocking but true: in the deployment of small cells, it's common for the lawyers to get more money than the radio vendors. Mobile operators need to negotiate blanket agreements with cities, to gain access to thousands of streetlights or other locations in one shot. Negotiating one site at a time will sink the business case.
7. **Site Rental**. Any radio unit that uses a rented space on a tower will see an increase in monthly rental fees. The vendors are integrating active massive MIMO arrays with passive FDD antennas, to avoid placement of a new antenna/radio box on the tower. Clearly it would be much more straightforward to use a separate box, but an additional unit would add roughly $2,000 per month to the cost of an American tower. Integrating active and passive antennas into a single, larger box should add $1,000 per month in rental cost.

Mobile Experts has two ways of looking at network costs. First, we take the above cost factors and we estimate the Total Cost of Ownership over an eight-year period, including assumptions for all cost related to site acquisition, radio deployment, backhaul, operations, and maintenance. Using this model, we can see the power of 5G. A 5G network can provide a huge increase in capacity, making use of the existing site and backhaul. In other words, most of the cost is related to the equipment itself, not the lawyers, tower owners, fiber suppliers, and trench diggers.

As a result, the impact of adding 5G capacity can be dramatic. The operator can reduce the cost of each Mbps of capacity from $3,000 (LTE) to less than $300. For wideband mm-wave systems, the cost of each Mbps should be as low as $50.

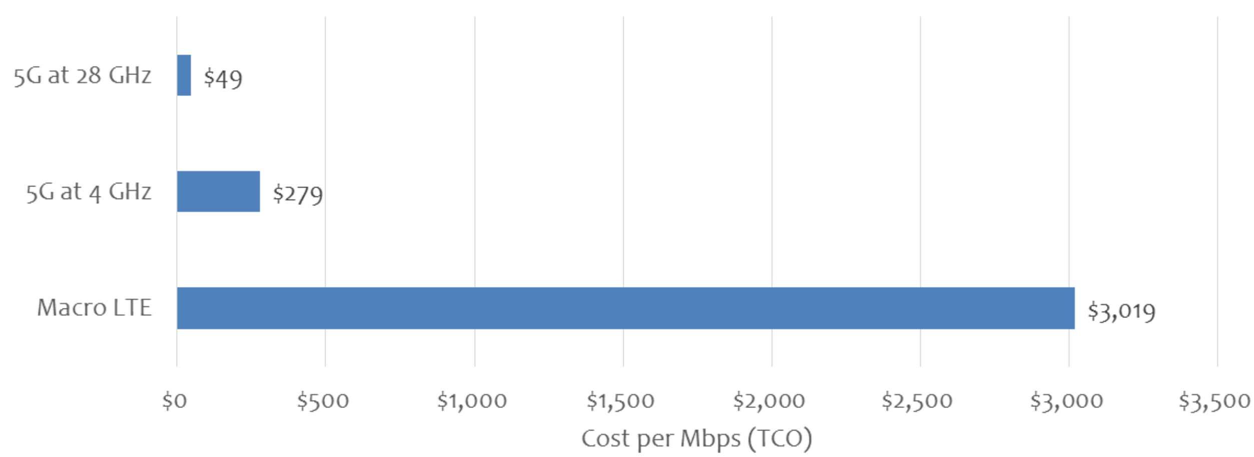

Chart 4: TCO per Mbps: Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts

Infrastructure—Cost per square kilometer

Looking at cost for capacity is the primary metric for operators, but they must balance the cost estimates per GB with cost per square kilometer. Additional capacity is extremely cheap at 28 GHz, but the cost to adequately cover a large area is ridiculously expensive.

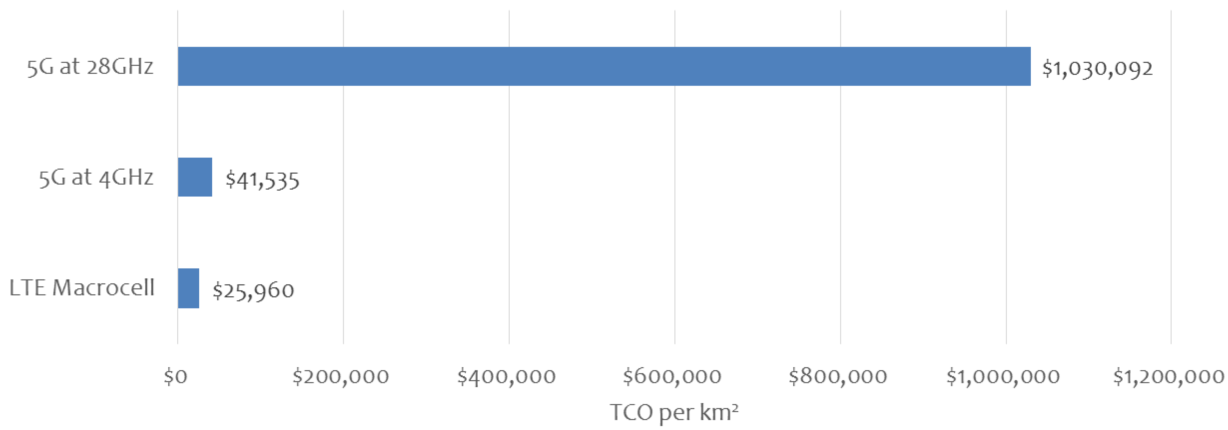

Chart 5: Cost per km²: Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts. Assuming 64T64R for both 5G networks

Putting it all together, we find that the choices for 5G infrastructure present some great opportunities for cost reduction, and a future growth direction. In the chart below, the 28 GHz systems shown so far between +56 dBm and +60 dBm have great potential as a high-capacity layer in the mobile network because the cost per Gbps of capacity is quite low. On the other hand, 5G networks at 3.5 GHz will have low cost of coverage (only $23,000 per square kilometer, comparable to LTE) while providing almost 10X improvement over a 2T2R LTE macro network in terms of cost per Gbps ($3,000 vs $300).

Of course, the ideal case is to achieve both low cost/km2 and low cost/Gbps. There are two possibilities:

- Higher EIRP in a 28 GHz network would provide longer outdoor range and wider coverage for a high-capacity radio. Higher power is possible with a change in semiconductors (for example, using GaN amplifiers instead of silicon). However, some feasibility challenges remain with regard to propagation in a cluttered environment. Penetrating the walls of buildings will remain a problem, even with a 6 dB boost in EIRP.

- Higher spectral efficiency in a 3-4 GHz network could also improve on its cost per Gbps. One possibility here is to use higher order MIMO arrays, but the practical problem is that a 64T or 128T array at 3 GHz will be larger than a typical tower can accommodate.

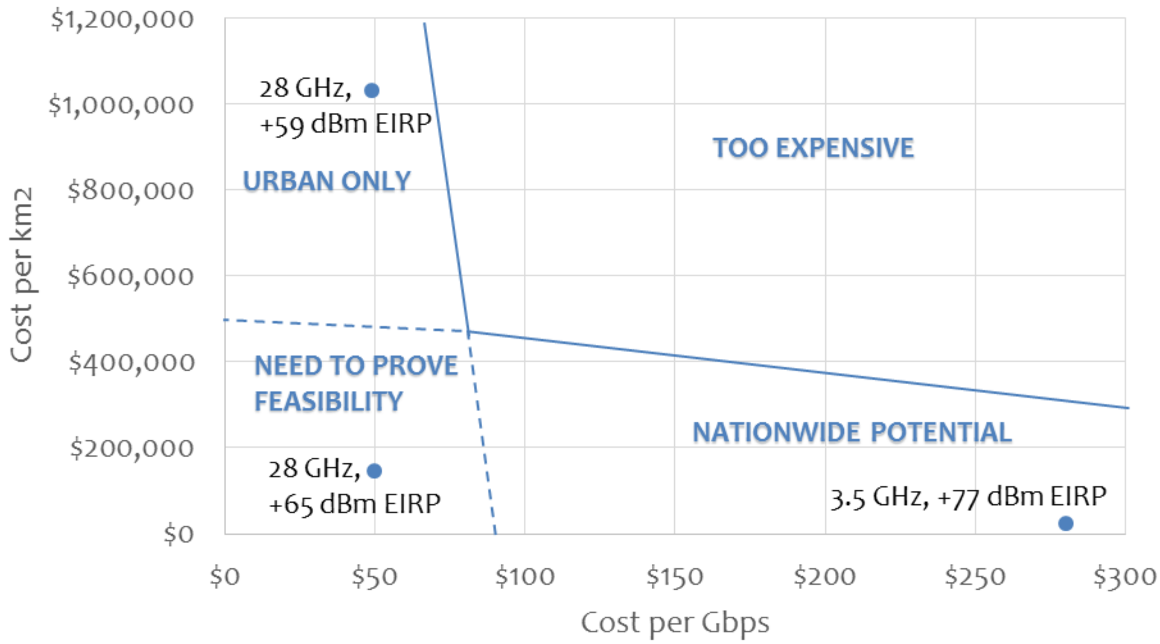

Chart 6: Cost of Coverage vs. Cost of Capacity for 5G

Source: Mobile Experts.

Infrastructure—Cost per GB delivered

Looking the cost of capacity and the cost of coverage are great ways to illustrate the strengths of each technology….but neither of these metrics accurately reflect the real-world situation for operators. In fact, real networks are a combination of coverage and capacity.

To create our forecast, Mobile Experts estimates the traffic density throughout mobile networks, to understand which areas will need upgrades of new technologies. LTE networks in urban pockets of Asia and North America now exceed a level of 0.05 Gbps/km2/MHz on a daily basis, and at this level we can see a clear business case to install additional capacity at 3-5 GHz. Above a traffic density level of 0.1 Gbps/km2/MHz, we see a clear business case for capacity at 28 GHz.

In other words, in places where the demand is highest, operators can install 5G equipment and actually realize the lower cost that we estimated. To be clear, network utilization is a key figure, and each operator has a rule of thumb that they follow, to only install new equipment when it will be utilized at a minimum level.

Following this logic, we make estimates of the utilization of the network for LTE and 5G, to illustrate the level of utilization that is required to make 5G deployment viable. In general, RAN equipment is typically utilized at a level of about 10% of its peak capacity, accounting for imperfect radio conditions, slow times of the day, and many other factors.

Assuming 10% utilization for macro network solutions, and lower utilization for small cell solutions, we see that the actual traffic delivered is still much cheaper for 5G solutions than for LTE solutions. The cost for each GB actually delivered can be less than $0.10 for 5G at 28 GHz, for a hotspot location that can utilize a high level of data consistently.

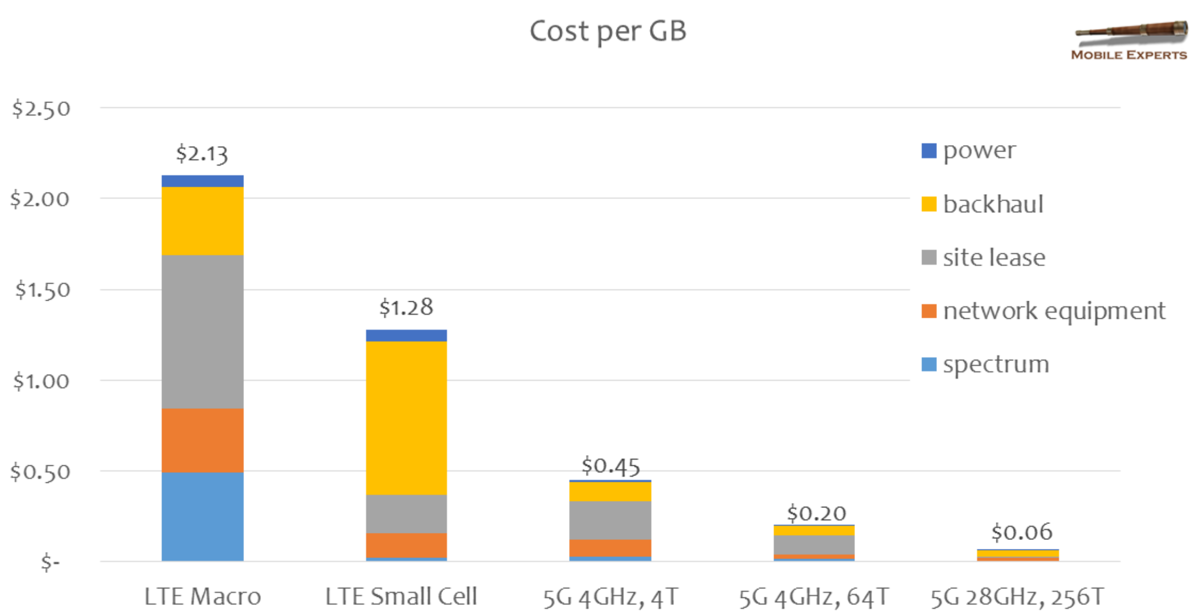

Chart 7: Cost per GB Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts

Fixed-Wireless CPE Cost

Development of CPEs for mm-wave systems have advanced dramatically, and attention to this opportunity by Qualcomm, Intel, and other semiconductor players has brought down the cost significantly. Key factors in the cost equation include:

- **Massive MIMO sub-arrays.** At 28 GHz, vendors are using up to 32 antenna elements in order to get very high antenna gain from the CPE. This means more complex radios and beamforming algorithms. The CPE will require a basic size to support the antennas, beamforming and baseband processing, and the power supply.
- **Semiconductor integration**. Compared with low-volume LMDS equipment from the 1990s, the BOM for these components will be quite inexpensive. We anticipate tight integration of the RF solution with the antenna elements and the up/downconverter to create an RF solution in the range of $30 or so. Possibly significantly less, depending on volume.
- **Indoor vs. Outdoor.** With high-gain antennas on the AP and the CPE, more than half of Verizon's field trial units can use an indoor CPE. This means that the unit doesn't need to be weatherproof.

- **Truck rolls.** Indoor CPEs with zero-touch configuration can avoid the expense of a visit by a technician. Rural fixed-wireless operators report an average cost of $200 per truck roll. This sounds low, but we've used this figure in our estimates.

Overall, we estimate the cost of an indoor CPE to be about $250, based on a semiconductor BOM of about $100. An outdoor unit should cost about twice as much, or about $500. The operator will need to carry the $200+ cost of a truck roll for outdoor units, and we expect some customer service cost associated with all CPEs, despite the intention to offer a zero-touch solution. These connections will be tricky, and consumers will not place the CPE near a window as instructed.

Handsets and Tablets

Handsets will be a difficult challenge for 5G above 6 GHz, so we expect most handsets to implement 5G only below 6 GHz, with mm-wave radios only in premium models. For now, we have two cost estimates:

1. A handset or tablet with a "simpler" 5G RF front end below 6 GHz (assuming 4 antennas) is likely to include a few RF components, plus the antennas. Assuming that smartphones will quickly reach volume of 100M or more, justifying integration of modules and antennas, the additional BOM cost added to the smartphone will be in the range of $5.00.

Component	Number per phone	Cost per component
Antenna	4	$0.05 (assuming integrated with existing LDS antennas)
Complete Front End (PA/Filter/Switch for Tx)	1	$1.00
Diversity Modules	3	$0.15
Transceiver (additional bands)	1	$0.20 (additional cost)
5G Modem	1	$2.50 (additional cost)
		$4.35 total

Figure 46. Additional BOM cost for 5G in mobile devices, 3-4 GHz

Source: Mobile Experts

2. A handset or tablet with 5G at 20-40 GHz will become more costly. The mm-wave radios must be positioned very close to the antennas, and the antennas must be widely spaced on the outside corners of the device because a hand covering one antenna must not be allowed to cover a second antenna array.

   In fact, the monetary cost of these modules may be secondary to the inconvenience of placing mm-wave modules at key locations on the handset. Top-tier handset OEMs have recently assigned industrial-design engineers to work out these "keep out" zones, so the signs are currently positive. However, the RF suppliers should realize that even the space taken by tiny mm-wave components is very precious on a smartphone.

Here’s a rough breakdown of the likely BOM costs for a mobile 5G implementation at 28 GHz:

Component	Number per phone	Cost per component
Antenna/PA/Switch/Downconverter module, 8 RF paths per module	4	$1.00 per module
Transceivers	2	$0.5 each
Modem	1	$3.00 (additional cost for higher bandwidth)
		$8.00 total

Figure 47. Additional BOM cost for 5G in mobile devices, 28 GHz

Source: Mobile Experts

9 5G MARKET OUTLOOK THROUGH 2025

During the past year, Mobile Experts has dramatically increased our forecast for 5G. We have not changed our view of the economics or the ROI/business case for mobile operators….but we have seen the signs that the Chinese government simply doesn't care about ROI for this project, and they will be investing heavily.   As a result, our market forecast for the USA/Korea/Japan/Europe has remained a gradual and thoughtful deployment, but we have added a HUGE deployment in China on top.

The resulting profile of deployment will be unusual over the next 7 years. We expect hundreds of thousands of 5G sites to be deployed in 2020-2023, and then the Chinese "surge" should come to a close, while many countries in the world are just starting to ramp up. (Note that about half of our data sources reflect numbers that are HIGHER than we show here for Chinese deployment. We have scaled back the most aggressive inputs based on our expectations for practical deployment issues).

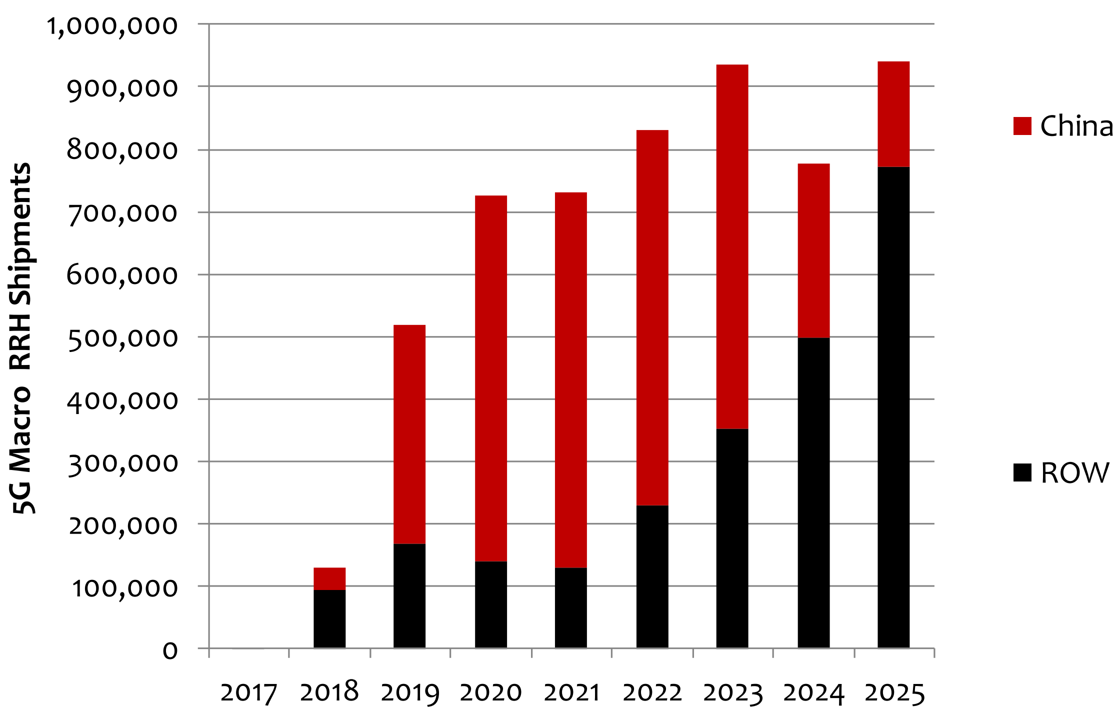

Chart 8:   5G Macro RRH units shipped, China vs. Rest of World, 2017-2025

Source: Mobile Experts

Outside of China, our forecast assumes that mobile operators will make rational decisions about where to deploy 5G, based on traffic density, ARPU/revenue, and the benefits of 5G in terms of reducing cost per GB. The Chinese surge will be important, because it will drive economies of scale into the supply chain and will make 5G radios and handsets possible more quickly for everyone else.

It's important to note that 5G deployment will look quite different than 2G/3G/4G deployment for many operators. In all previous generations, nationwide networks were deployed to cover 70% of the population or more, to support nationwide marketing campaigns. In some cases, 5G will follow this path, as with the 600 MHz deployment for T-Mobile USA. However, many other operators will choose very specific "islands" of coverage, because 80% of the coverage area in their network will not create any profit from a 5G network at this time. The traffic density and revenue density of the network is concentrated in urban centers, so we will see many 5G networks focused only on urban centers for a few years.

Infrastructure Outlook

To stay consistent with our tracking of the Macro and Small Cell markets, we have broken our 5G forecast into two major segments:

- High power RRH shipments: Above a power level of +52 dBm, the operator is targeting "macro" level of coverage. Almost all of this high-power deployment will take place below 6 GHz due to the limitations of power in the millimeter-wave bands.
- Low power RRH shipments: Below +52 dBm, the mobile operator will be targeting small coverage areas for each site, so we treat this segment of the 5G market as an extension of the small cell market.

Note that in the past we have forecasted 5G FWA as a completely separate segment, but now we see the 5G FWA business re-converging with the mobile network in just a few years….so instead of tracking this segment as a third market altogether, we are now simply tracking FWA as one of the use cases of 5G deployment.

5G Macro Infrastructure

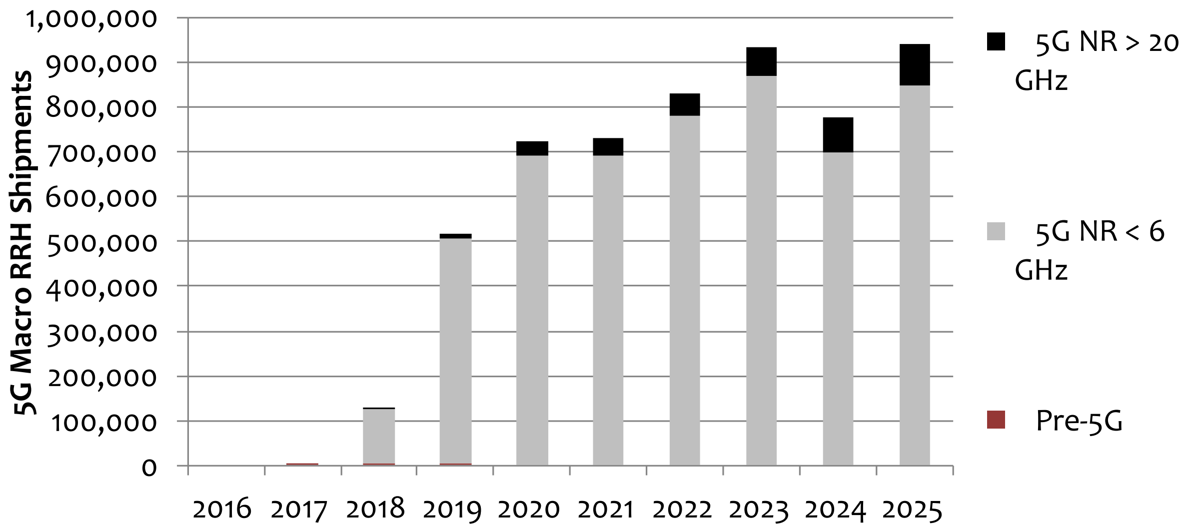

Chart 9: 5G Macro RRH units shipped, by frequency range, 2017-2025

Source: Mobile Experts

Looking closely at macro 5G deployment by frequency band, we see that the 3.5 GHz and 4.8 GHz bands will dominate the view due to the surge in China. American LMDS bands at 28 GHz and 39 GHz will dominate the mm-wave market for the near term. Other bands, such as 3.3 GHz, 3.7 GHz, and existing 1-2 GHz 3GPP bands will grow at a measured rate as individual countries/operators will choose these bands gradually over time.

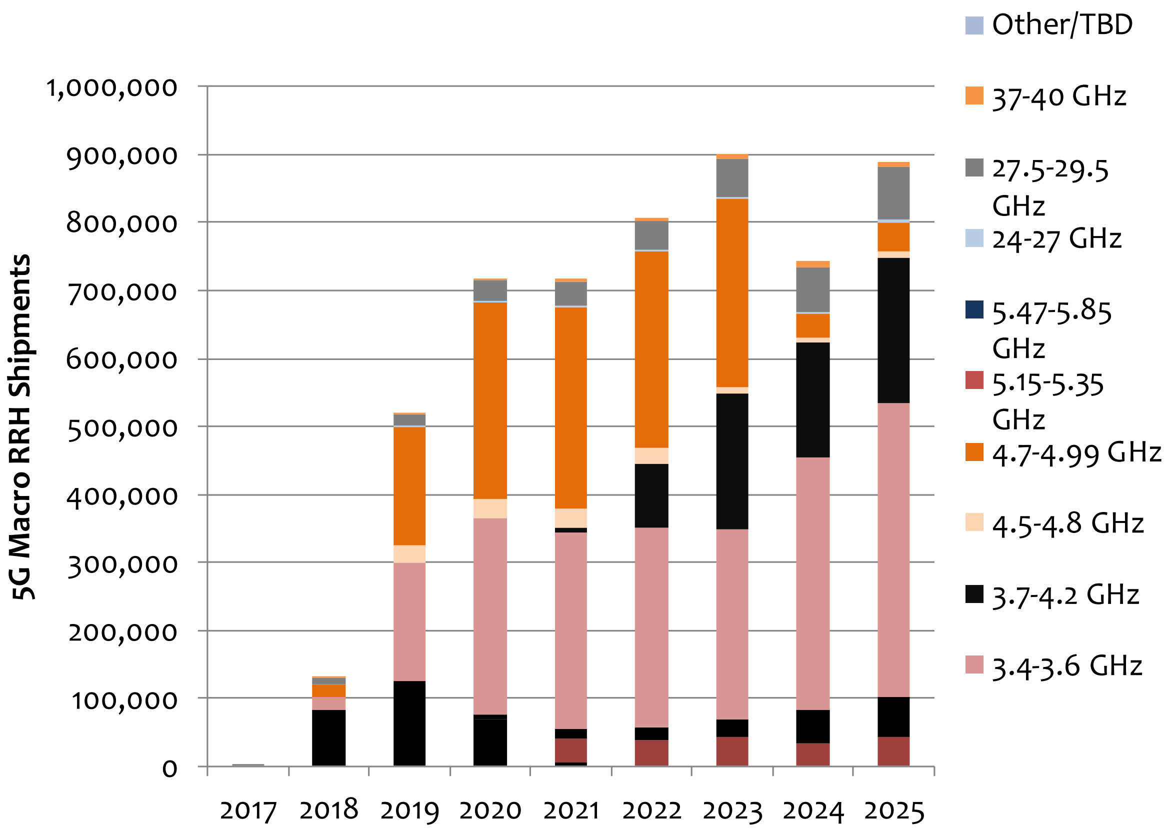

Chart 10: 5G Macro RRH units shipped, by detailed frequency band, 2017-2025

Source: Mobile Experts

5G Small Cell Infrastructure

Low power RRH shipments will include units below 6 GHz as "small cell densification" for the 5G macro network, and also low-power RRH units in the millimeter-wave bands. Lower-power infrastructure in the 28-39 GHz bands will be used in semi-indoor applications and in urban locations where both azimuthal and elevation steering are desired. (Generally, low-power units above 20 GHz will use silicon amplifiers with EIRP below about +50 dBm, and high-power RRH units will have EIRP in the range of +65 dBm using GaN amplifiers).

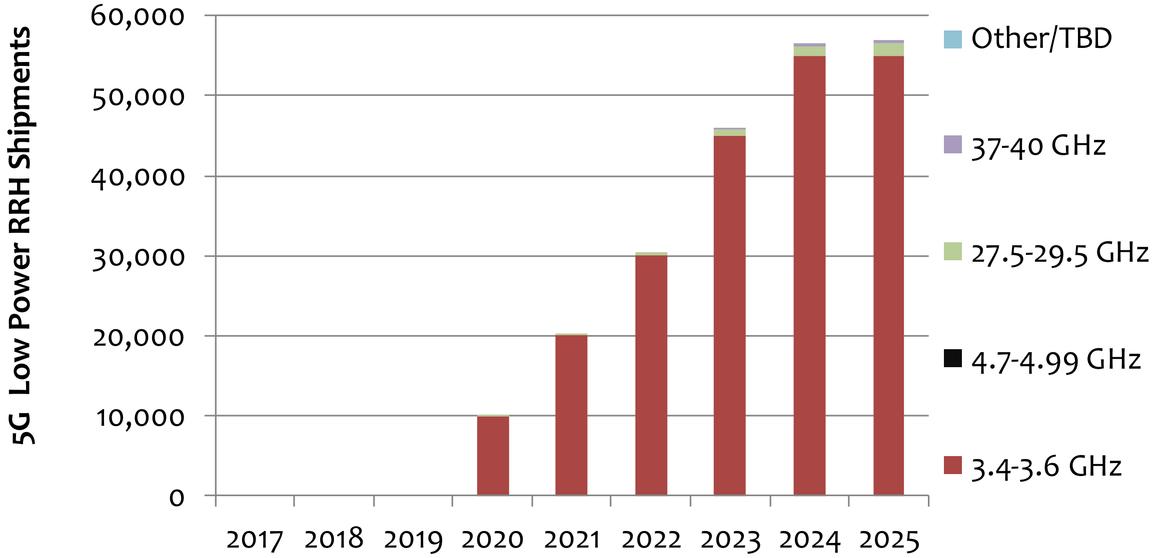

Chart 11: 5G Low Power RRH units shipped, by frequency band, 2017-2025

Source: Mobile Experts

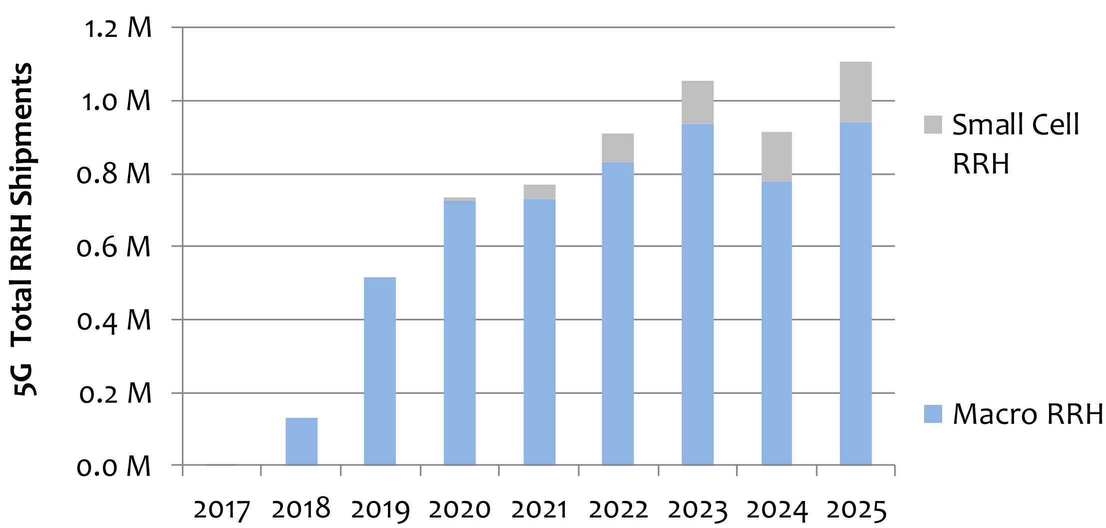

Chart 12: 5G Total RRH units shipped, Macro vs Small Cell, 2017-2025

Source: Mobile Experts

The 5GTF specification will dominate the deployment at 28 GHz, but other forms of a pre-5G standard will start shipping in larger quantity in China during 2018. By the end of 2019, we expect all operators to adopt the 5G NR standard. Note that we have shown the 5G SIG (Korea Telecom) deployment on our chart here, but the numbers are quite small with about 30 RRH units to cover specific Olympic events and three sites in Seoul.

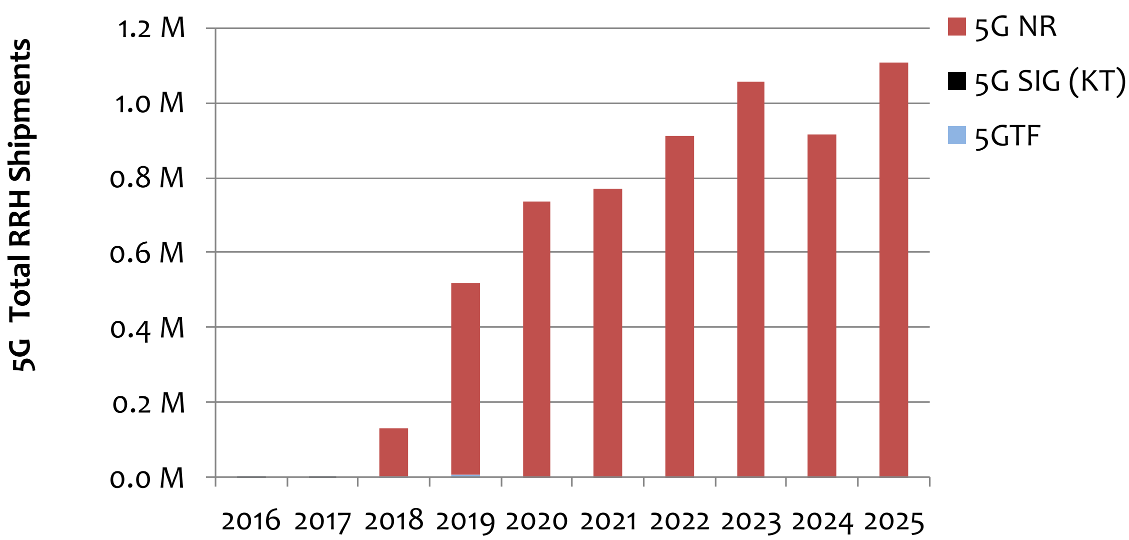

Chart 13: Pre-5G and 5G RRH units shipped, by standard, 2017-2025

Source: Mobile Experts

At this time last year, Verizon was noncommittal about 5G NR, but of course the idea of Verizon continuing to support their own proprietary air interface would be ridiculous. Verizon has now admitted that they will converge with 5G NR, and we predict that 2020 shipments will mark the changeover point. This means that some 11,000 RRH units will ship using the 5GTF format, and some of these will need upgrades to 5G NR hardware in the future.

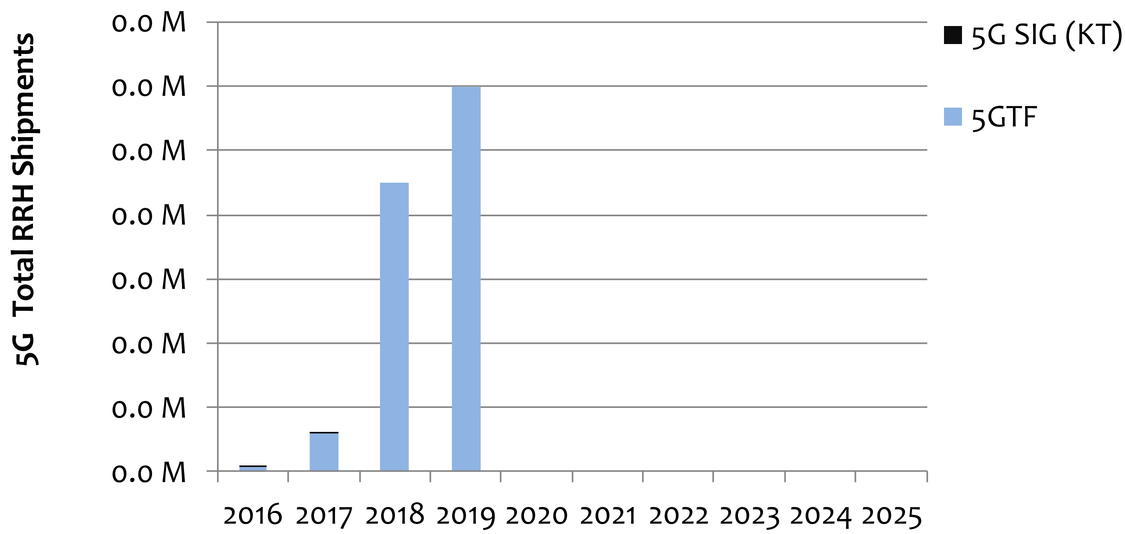

Chart 14: Pre-5G RRH units shipped, by standard, 2017-2025

Source: Mobile Experts

The fixed-wireless application currently dominates the 5G conversation in the USA, but over time we expect any deployment by a mobile operator to support some level of mobility. A mobile standard can be used for FWA, but an FWA standard cannot be useful in a mixed environment with some mobile users.

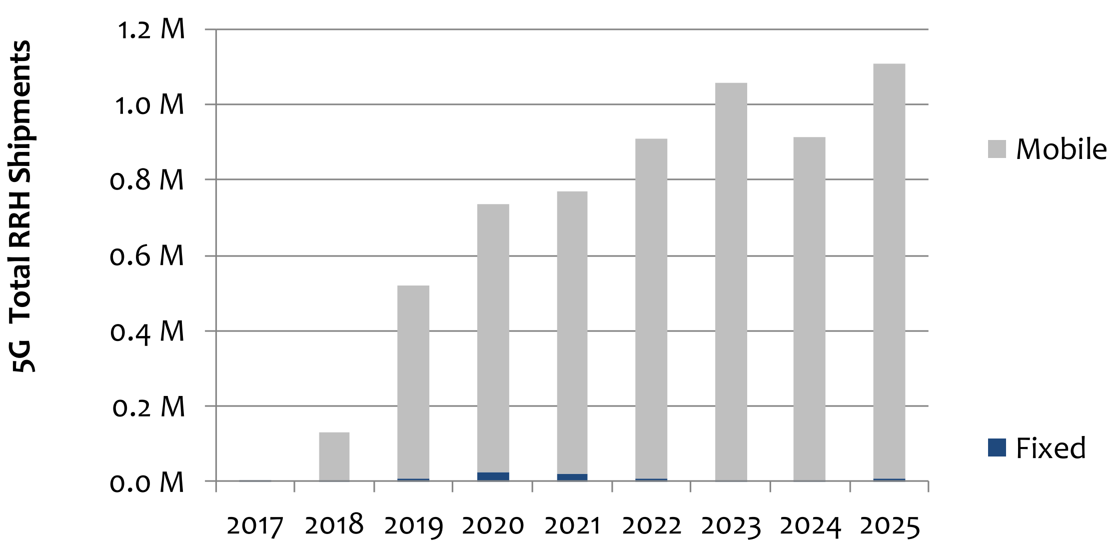

Chart 15: 5G RRH units shipped, by mobile vs fixed, 2017-2025

Source: Mobile Experts

Non-standalone 5G networks are the default configuration for mobile operators, because the LTE core and LTE control signaling are an easy way to begin 5G operations. Over time, most mobile operators want to migrate to stand-alone networks in order to encourage competition between network vendors. Most of the near-term 5G deployment will use a "5G Enhanced Packet Core" or "5G EPC" which is a software extension on an existing 4G EPC. We anticipate mobile operators performing trials with 5G next-generation core networks in 2018 and 2019, with deployment in 2020. In fact, the chart below is somewhat misleading because a great deal of the "NSA" deployment in the 2018-2020 timeframe will be upgraded to "SA" via software after its initial deployment….so by 2023 we expect at least 30% of the 2018-2022 NSA radios to be supported by 5G next-gen core networks.

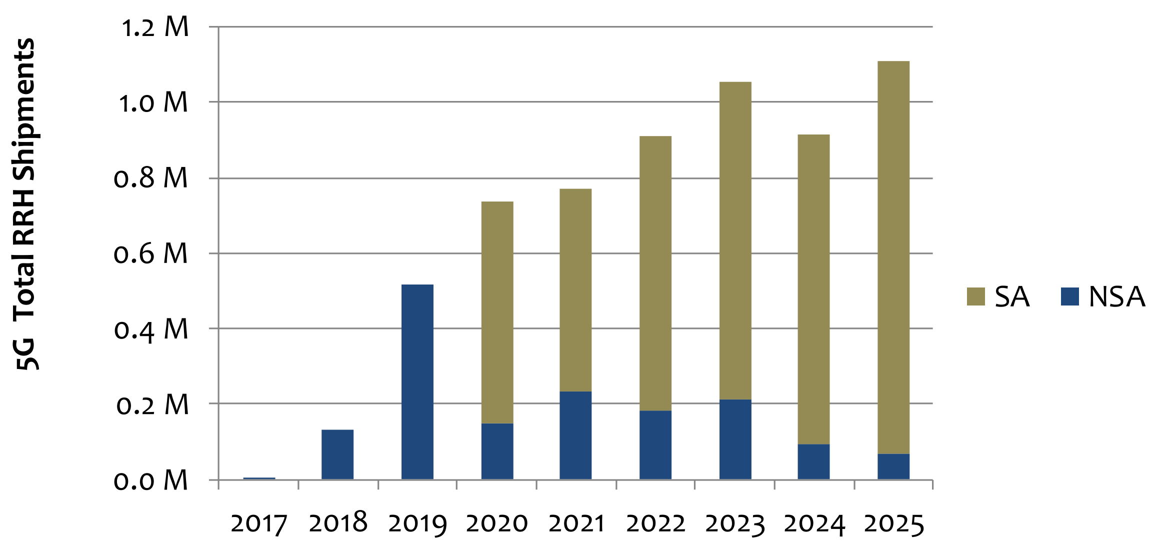

Chart 16: 5G RRH units shipped, by NSA vs SA, 2017-2025

Source: Mobile Experts. "NSA" or "SA" status indicated at time of deployment.

5G Handsets, Tablets, and Broadband IoT devices

Modems are available today for 5G NR, so the availability of 5G handsets and other devices should move very quickly. Samsung has already demonstrated 5G NR operation in a tablet at 28 GHz, and Qualcomm has shown prototype RFICs with integrated front ends/antennas at 28 GHz.

We will see rapid adoption of 5G technology in China, as the existing network quality is poor on 4G and most Chinese consumers have shown an appetite for upgrade to more capable smartphones. So handsets with radios at 3.5 to 5 GHz will become standard in China very quickly, and will follow in global SKU models such as iPhone and Galaxy phones. In this way, the impact of China will be larger than the population of China itself.

In mm-wave frequency bands, we now expect some mobile devices to emerge. We have already seen tablet and smartphone prototypes that work at 28 GHz. While this radio will be expensive and power-hungry, we can expect a premium tier of the market to pay for multi-gigabit bandwidth.

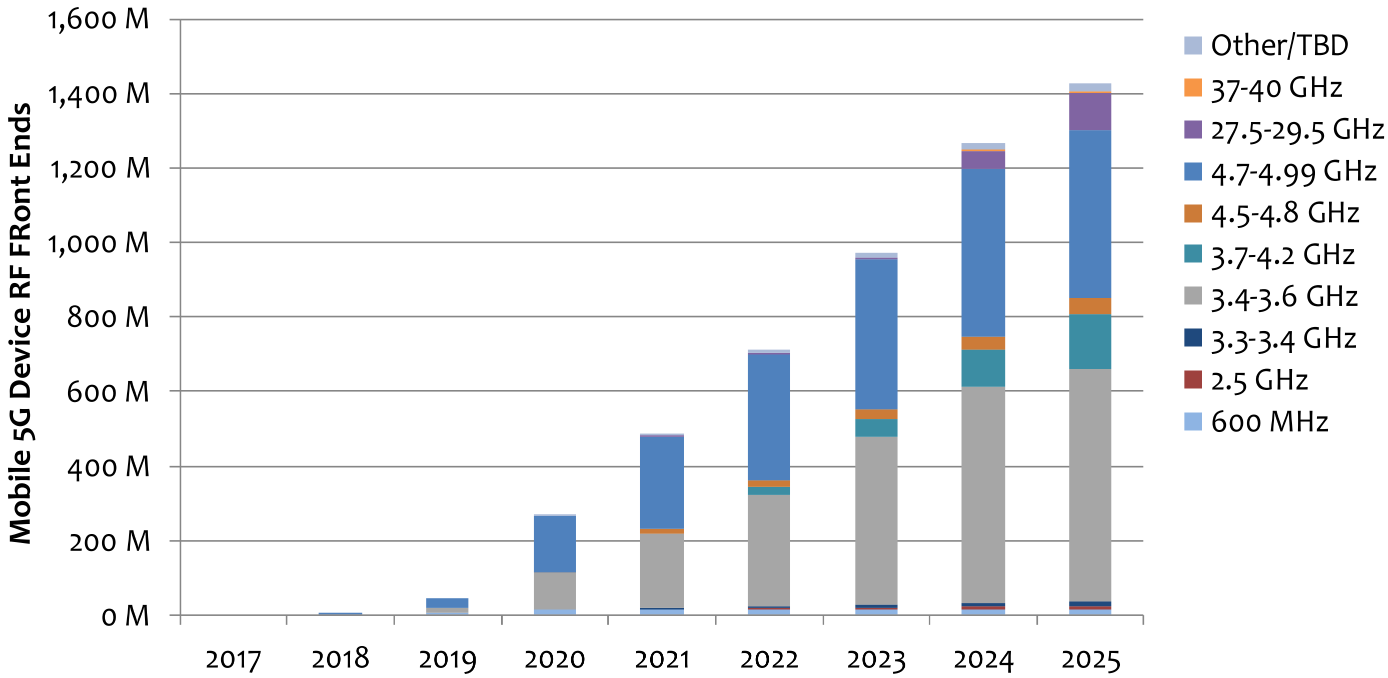

Chart 17: 5G Mobile User Devices, by the main mobile 5G band, 2017-2025

Source: Mobile Experts

The vast majority of mobile devices using 5G NR will be smartphones, based on the strength of 3.5 to 5 GHz adoption in global phone models. We also anticipate that 5G NR could replace Wi-Fi as the primary connectivity in tablets/PCs, in locations where 5G coverage is widespread, and where 5G tariffs are lower than $0.20 per GB. Until this tipping point is met, we expect 5G hotspots to be used by early adopters in the PC market.

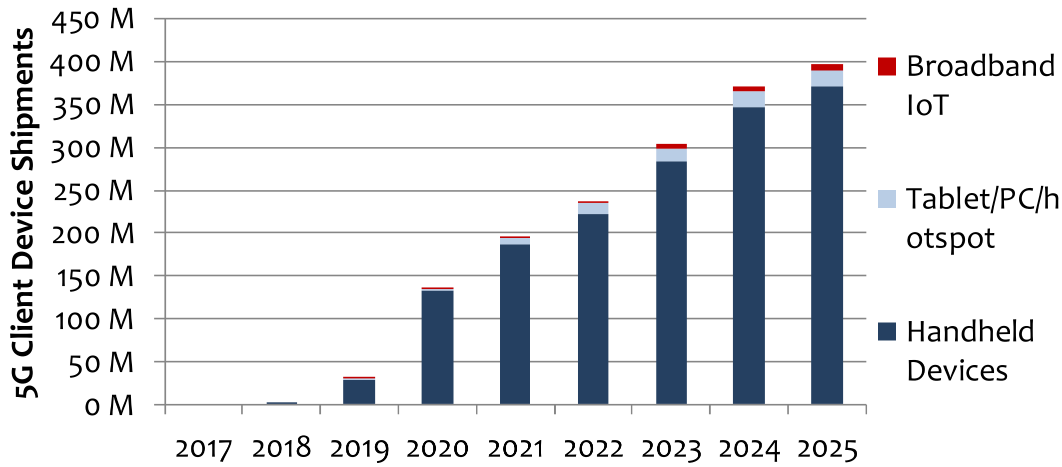

Chart 18: 5G Mobile User Devices, handset vs tablet/PC vs Broadband IoT, 2017-2025

Source: Mobile Experts

Broadband IoT devices such as drones, security cameras, and autonomous vehicles will constitute a relatively small fraction of total 5G client devices. Note that we have excluded IoT devices that simply use the low latency or high reliability of the 5G network….in the scope of this study we are primarily concerned with broadband applications of 5G networks.

CPEs for Fixed Wireless Access

In the fixed-broadband application, the opportunity is growing. Rural areas in many countries support a population of people that are left out of the Internet age, and they want to participate online with everybody else. Today, we see 5G FWA plans for urban customers that are underserved by cable and DSL options. Over time, we expect to see LTE FWA transition to 5G NR as well, in frequency bands ranging from 450 MHz through 5 GHz. In this way, the number of 5G CPEs will grow.

Note that one counter-trend will offset the growth of 5G FWA in sub-6 GHz bands. The initial deployment of FWA in mm-wave bands using 5G NR will start to convert into mobile deployments, so the initial surge of 5G NR FWA at 28 GHz will slow to about 20,000 CPEs per year, representing the typical market for enterprise fixed connectivity.

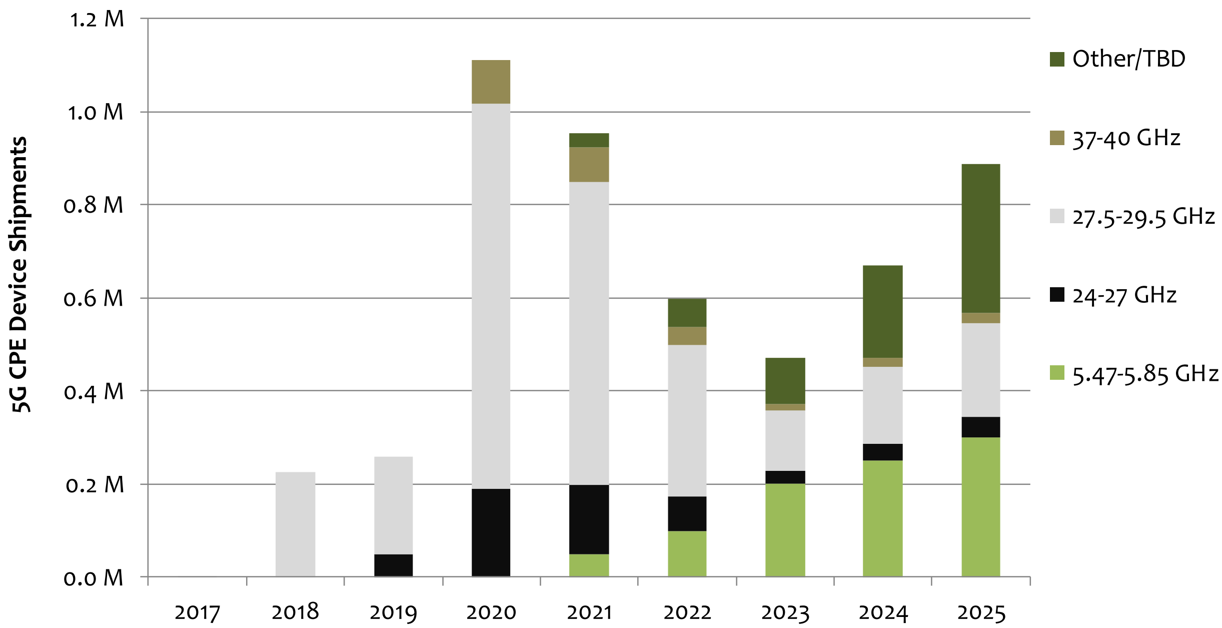

Chart 19: 5G FWA CPEs, by the main mobile 5G band, 2017-2025

Source: Mobile Experts

10 COMPANY PROFILES

Ampleon

Ampleon supplies RF power transistors using LDMOS and GaN for LTE infrastructure today. This company was spun out from NXP Semiconductors, during the time that NXP was acquiring the RF power business of Freescale, and regulatory agencies would not allow a combination of the two competing product lines. Ampleon has a strong market share position and should be expected to show up with competitive LDMOS and GaN products in the 3-5 GHz band.

Analog Devices

ADI is a strong supplier for ADCs and DACs in mobile communications, and with their acquisition of Hittite Microwave they have the ability to put together the RF CMOS transceivers and compound semiconductor front end components in heterogeneous assemblies.

Anokiwave

Anokiwave had an early headstart with mm-wave arrays, and has been able to use its extensive experience in radar systems for military applications to realize effective beamforming in the 5G case. Anokiwave is among the first companies to reach production volumes, with many prototype 5G systems based on their RFIC. The company works with both SOI and SiGe technologies.

Broadcom

Broadcom/Avago has supported millimeter-wave markets for over thirty years, with a strong amplifier capability. The company also has strong filter capability which might apply at 3.5-6 GHz but probably not at mm-wave frequencies.

Commscope

Commscope is an antenna supplier based in the USA. The company has a reputation for high quality and high performance. Nokia and Commscope are working together to manufacture 5G Massive MIMO arrays with integrated radios.

Ericsson

At Ericsson, radio technology has always been a strength, and the company comes into the 5G market with deep capability in the integration of the radio, antenna, and baseband processing. Ericsson has also invested heavily in virtualized core networks and Cloud infrastructure to support the mobile applications. Ericsson has emerged as one of two suppliers supporting production deployment at 28 GHz for Verizon.

Fujitsu

Fujitsu provides mobile infrastructure and client devices for the Japanese market, and has shown some interesting fixed-wireless solutions at 28 GHz recently. The company has developed the concept of Distributed MIMO to achieve very high throughput in a small area, using a widely dispersed network of simple RRUs.

GlobalFoundries

GlobalFoundries acquired the IBM fab with strong capabilities for SOI and SiGe technologies. GlobalFoundries now has a partnership with Anokiwave for mm-wave RFICs, and also other customers that have used their fab to develop 3-5 GHz 5G RF front end devices.

Huawei

Huawei is likely to be the dominant supplier for 3.5 GHz 5G systems, with a clear advantage in the Chinese market. The company has already deployed ten thousand mMIMO systems at 2.5 GHz for TD-LTE and has a long list of field trials ranging into the mm-wave range as well.

IBM

IBM has partnered with Ericsson to develop a SiGe phased array capability for mm-wave radios, and together the companies have announced their intention to commercialize the technology for the base station mMIMO application.

Infineon

Infineon has strong SiGe capability, and for example has produced a radar-on-a-chip products for automotive applications at 24 GHz and 77 GHz. Infineon combines capability for SiGe, BiCMOS, GaN, and RF CMOS, so they have the ability to put together a multi-chip module with complete radio functionality. Infineon has agreed to sell the LDMOS power transistor business to CREE (Wolfspeed), as the US Government prevented Infineon from buying the US operations of CREE's Wolfspeed business unit.

Intel

Intel recently introduced a line of commercial 5G NR Modems so that they are in position for the growth of 5G NR handsets. For 5G radios, Intel is focused on antenna/RFFE/transceiver/modem development for the handset, using bulk CMOS to achieve impressive performance in mm-wave frequencies but at lower power than most operators want.

Of course, Intel is also very much involved with baseband processing and the implementation of Virtualized RAN systems using the X86 architecture on standard servers to run network software. The two business areas are separate but Intel's strong presence in the Cloud RAN area gives them a window into upcoming 5G deployments.

Kathrein

Kathrein-Werke is an antenna supplier based in Rosenheim, Germany. The company has a reputation for high quality and high performance. Nokia and Ericsson have both engaged Kathrein to construct antenna systems with integrated radios for 5G applications.

MACOM

MACOM has put together a product line of GaN power transistors for application at 3-5 GHz for 5G infrastructure applications. MACOM's plastic packaging is set up for low cost in a massive MIMO configuration. The company has made a deal with ST Microelectronics to fabricate GaN on 6" to 8" silicon wafers, for another cost step and to support the huge scale in terms of the number of devices needed for 5G arrays.

Microsemi

Microsemi produces integrated single-function modules using SiC, SiGe, GaAs, GaN, and InP, with capabilities up to 140 GHz. Microsemi also (via acquisition of Symmetricom) plays an important role in network synchronization, and we expect them to benefit from the tighter phase/frequency precision requirements imposed on the overall network, which will drive new sync sales.

Movandi

Movandi is a start-up company in California that has developed a Massive MIMO array at 28 GHz. The company was able to develop prototype hardware very quickly with impressive performance,

NEC

NEC is a strong supplier of telecom equipment in Japan, and has developed base station and backhaul products to support 5G deployment. We expect most of NEC's RAN activity to be confined to the Japanese market, but their backhaul products as well as gateways and other solutions are seen more globally.

Nokia

Nokia is a strong base station vendor with a strong end-to-end product portfolio and a good integrated strategy for 5G. Nokia has already introduced 5G-capable baseband processing units so that today's shipments are software-upgradable to 5G NR. Nokia also has an innovate RFIC approach for 3-6 GHz 5G infrastructure applications.

Nokia has dropped out of the market for 5GTF hardware in the US FWA market, deciding instead to focus on 5G NR development.

Nuvotronics

Nuvotronics constructs steerable antenna arrays for military (radar) applications, and has experience with the integration of antennas, filters, power amplifiers, LNAs, and back-end processing in heterogeneous assemblies. Nuvotronics is in a good position to offer know-how to the industry when it comes to buried waveguide transmission lines, antenna arrays, and heat management in a very small mm-wave assembly.

NXP

NXP sells integrated modules for automotive radar applications at 77 GHz, and thus has a strong mm-wave development capability. NXP is developing high power transistors using GaN (as well as their legacy Silicon LDMOS products) which will be used in 3.5 GHz and other sub-6 GHz radio head deployment. The company has agreed to be acquired by Qualcomm, and we expect the transaction to be completed sometime in mid-2018.

Qorvo

Qorvo supplies GaN devices and several other compound semiconductor MMICs, with clear experience in both government and commercial markets. Qorvo is working with multiple OEMs on mm-wave 5G prototyping, using GaN devices.

Qualcomm

Qualcomm has moved quickly to put together 5G NR modems, which are available today for handset or other 5G device development. In addition, the company has RFICs available that integrate up/downconversion, power amplifier/LNA, and antennas at 28 GHz, with a thoughtful approach to the use of multiple mm-wave RFICs in a handset.

Qualcomm is in the process of acquiring NXP, and we expect this transaction to be completed in mid-2018. Broadcom has also made a hostile bid to acquire Qualcomm, and this prospect has been rejected multiple times. We don't expect the Broadcom/Qualcomm deal to happen.

Samsung

Samsung is trying to use 5G to break into the mobile infrastructure market, and has invested heavily in the network infrastructure area, in addition to the company's traditional strength in smartphones and other mobile devices. Samsung has deployed equipment in Korea under the 5G SIG format for KT, and has taken the lead role in Verizon's 5GTF deployment. In this way, Samsung currently stands as the reigning champ of 28 GHz infrastructure. Samsung's challenge will be to convince mobile operators to step away from their incumbent network vendors… this might be a challenge in NSA deployment so they will be pushing a change to SA.

Samsung clearly has a leading position in smartphones and tablets, and recently the company demonstrated a 5G video call over a tightly integrated tablet device.

Skyworks

Skyworks is developing RF-SOI devices for mm-wave communications applications, and also has extensive shipment history with millions of SiGe BiCMOS devices.

Sumitomo

Sumitomo is a leading supplier of power transistors using GaN material for 3G/4G base stations, and the company has experience with Wafer Level Chip Size Packaging (flip-chip mounting of one die on top of another die), with 80 GHz LNAs. Sumitomo is currently the leading supplier of power devices for the 2.5 GHz Massive MIMO deployment in TD-LTE. We expect Sumitomo to have an important role in the big ramp of 3.5 to 5 GHz infrastructure in China.

Texas Instruments

TI leads the market in providing Digital-to-Analog converters for radio systems, and has a strong position with the major network equipment providers, especially for the data converters in very wideband 5G radios.

Wolfspeed (CREE)

Wolfspeed is the #2 supplier of GaN power devices on the mobile infrastructure market, working closely with RFHIC in Korea to package the GaN devices for telecom customers. As GaN will be an important technology for 5G deployment at 3.5-5 GHz, we expect Wolfspeed to compete for modules and discrete power devices in 5G NR infrastructure. CREE has recently agreed to acquire Infineon's RF Power division, so the relationship with RFHIC may be changing.

ZTE

ZTE has been developing some interesting technology to estimate the mMIMO channel conditions in FDD mode where the uplink and downlink are very different. The company should not be discounted. ZTE is in a good position to capture major 5G market share with Chinese deployment leading the market in the 2019-2021 timeframe. The company is actively developing a 3.5 GHz radio/antenna solution today.

11 METHODOLOGY

For our 5G analysis, we are investigating the technology first, using a logical, analytical process. We have interviewed more than 35 mobile operators with regard to 5G plans, including:

- ***Why will the operator deploy 5G infrastructure***? What is the likely business case and does 5G make sense financially?
- ***What will the operator deploy*** to satisfy the business case? How widespread will the deployment be?
- ***Can the vendors meet the needs of the operators*** in terms of radio performance and virtualization of the network?

Our view of 5G as an overall generation of technology is developed in two steps. After the technology discussions and evaluation of what is needed and where it's needed, we evaluate the business case for 5G. In November 2017 we published some highly detailed business case scenarios to illustrate how 5G reduces cost per GB in the network.

Finally, we interviewed more than 30 semiconductor and component suppliers to understand the limitations of physics. Can silicon deliver high EIRP without too much heat load? What is the optimal configuration of Massive MIMO for power consumption? How much will mm-wave radios cost in a handset? These types of questions establish an understanding of what's possible with state-of-the-art hardware.

The bottom line: Our forecast is based on estimates of:

1. Traffic density and estimated numbers of sites that need 5G capacity upgrades to satisfy end-user demand;
2. Network cost calculations and estimates of how many sites have a positive ROI from 5G upgrades;
3. Cost estimates for CPE and mobile devices, and expected adoption rates;
4. Estimates of the ability for the supply chain to deliver large quantities of components in production.

12 APPENDIX: EXAMPLES OF M-MIMO AND 5G HARDWARE

Infrastructure examples below 6 GHz

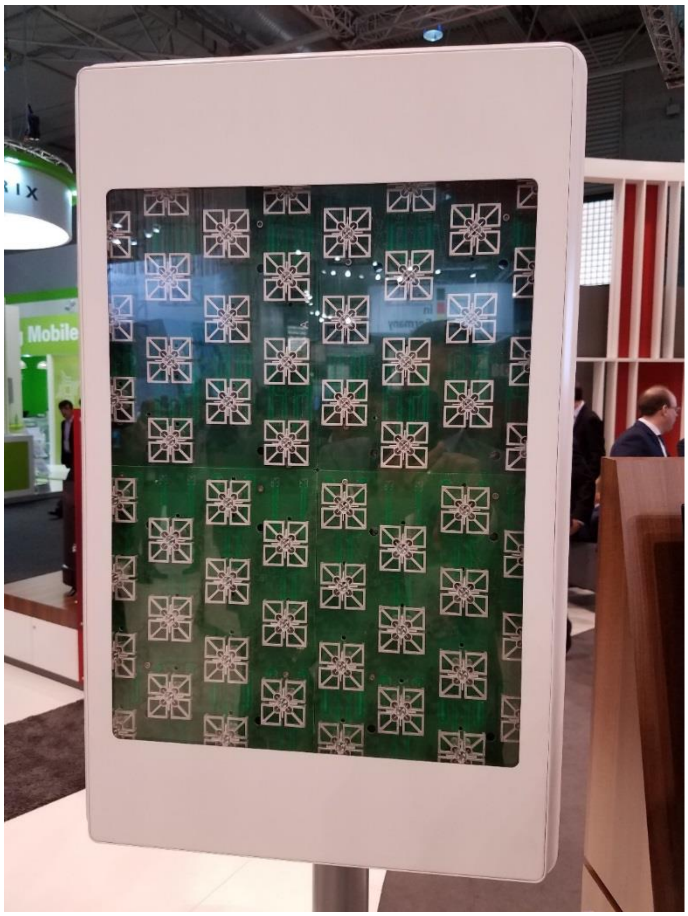

Figure 48. Huawei 2.6 GHz TD-LTE mMIMO array (trial with Vodafone)

Source: Mobile Experts (MWC 2017 photo)

Figure 49.   Huawei m-MIMO arrays at 3.5 GHz (32T vs 64T size)

Source: Mobile Experts (MWC 2018 photo).

Figure 50. Nokia 2.5 GHz m-MIMO array, 120W at 64T64R

Source: Mobile Experts (MWC 2018 photo).

Figure 51. Ericsson 3.5 GHz m-MIMO array, 200W at 64T64R (AIR6488)

Source: Mobile Experts (MWC 2018 photo).

Figure 52. Photo of ZTE m-MIMO array, 2.3 thru 3.5 GHz, 64T64R

Source: Mobile Experts (MWC 2018 photo).

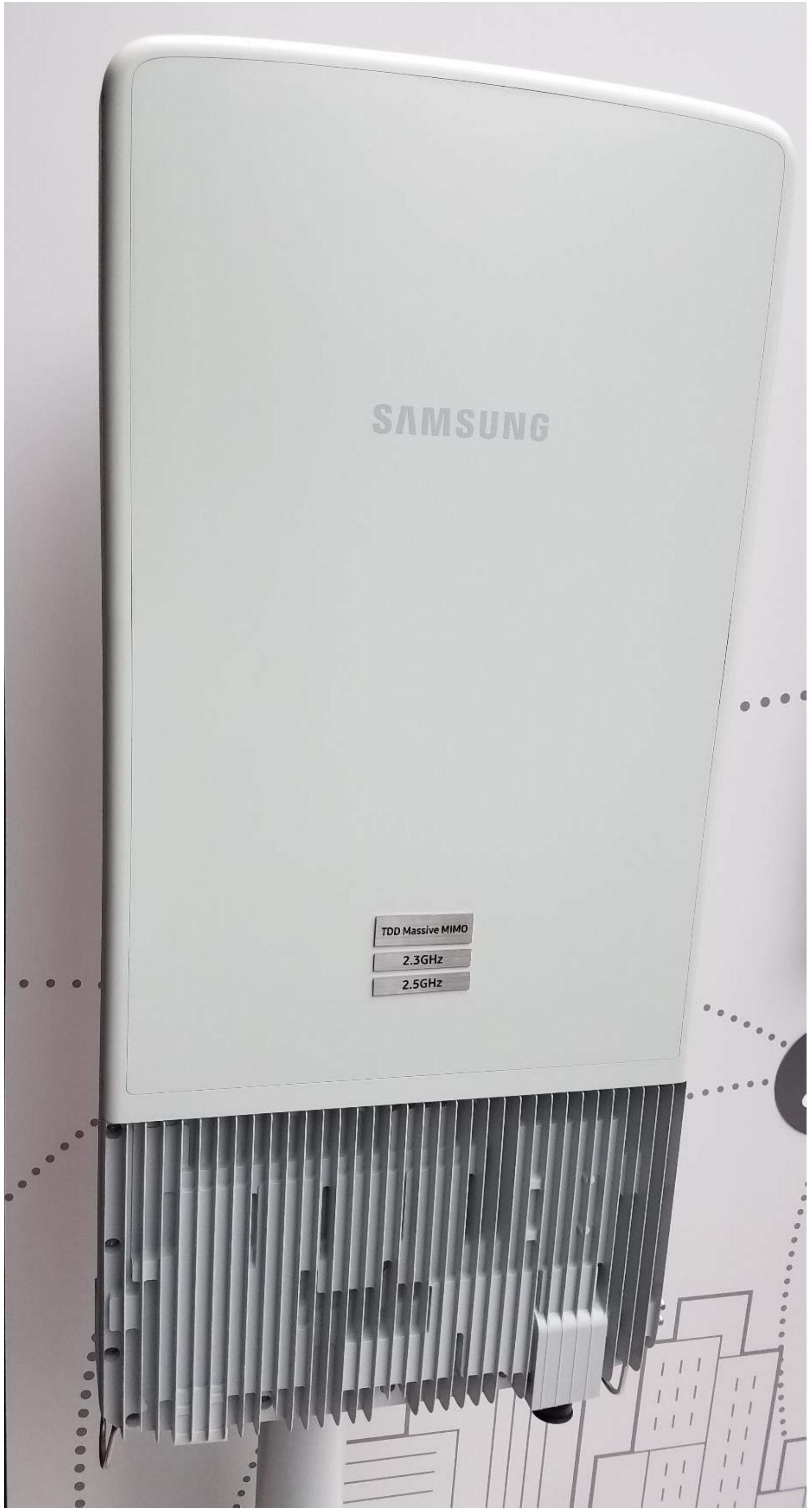

Figure 53. Samsung m-MIMO array, +52 dBm EIRP, 2.3 GHz or 2.5 GHz at 64T64R

Source: Mobile Experts (MWC 2018 photo).

Figure 54. Huawei dual-band m-MIMO array at 2.6 and 3.5 GHz (32T+32T)

Source: Mobile Experts (MWC 2018 photo).

Note the progress from 2017 to 2018 (dual band, taller unit with 32T instead of 64T)

Figure 55. Huawei m-MIMO dual-band array backside picture

Source: Mobile Experts (MWC 2018 photo).

Figure 56. Ericsson Dual-band m-MIMO array, 2.6 and 3.5 GHz at 100W each (AIR3252)

Source: Mobile Experts (MWC 2018 photo).

Figure 57.   Commscope dual band m-MIMO array, Band2/Band4 with 16T16R active arrays

Source: Mobile Experts (MWC 2018 photo).

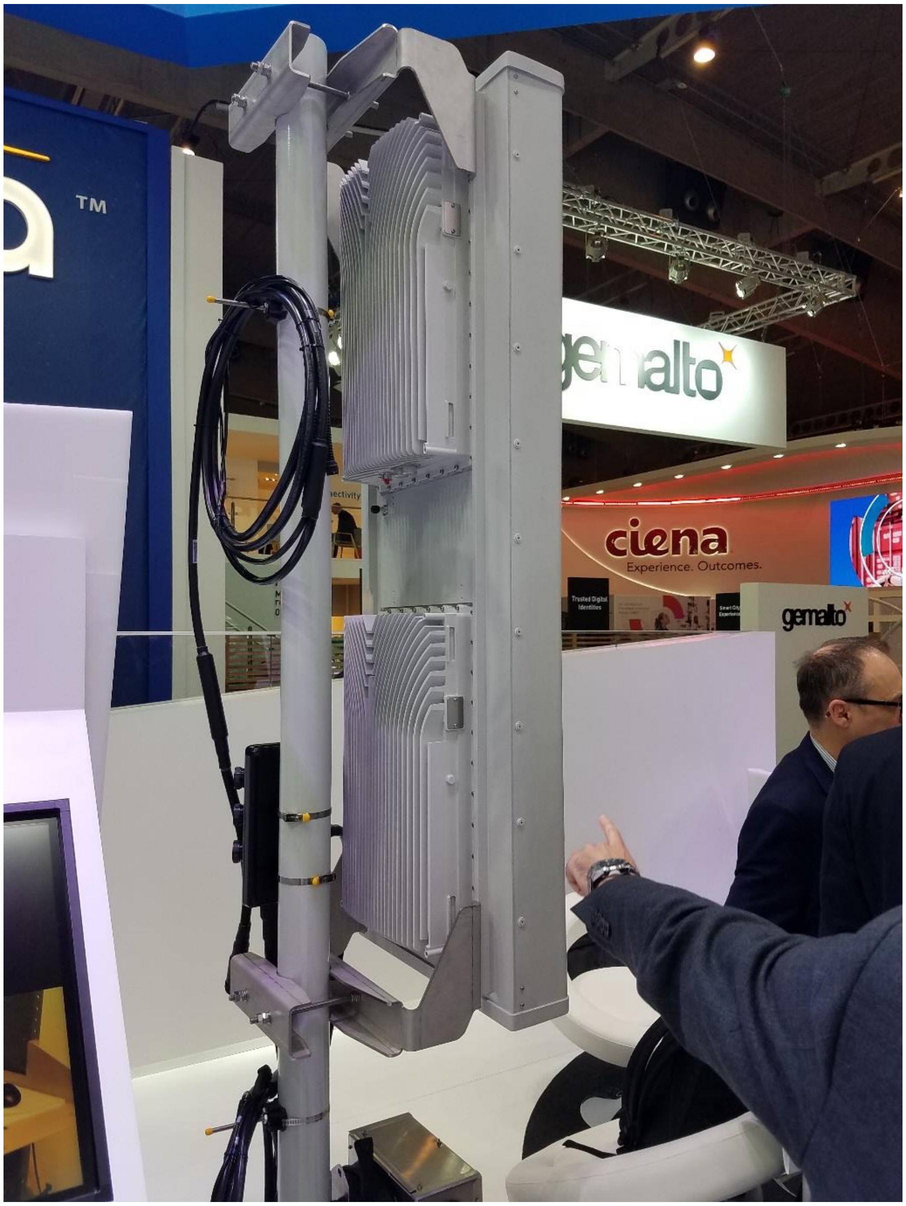

Figure 58. Commscope dual band m-MIMO array, back side showing Nokia's replaceable radios

Source: Mobile Experts (MWC 2018 photo).

Infrastructure examples above 20 GHz

Figure 59. Samsung mMIMO array, 28 GHz band (used in Korea Olympics)

Source: Mobile Experts (MWC 2018 photo)

Figure 60. Samsung RRH at 28 GHz, as shown in 2017

Source: Mobile Experts (MWC 2017 photo)

Figure 61. Samsung 2018 RRH at 28 GHz, 4x256T for four streams

Source: Samsung, 2018 version

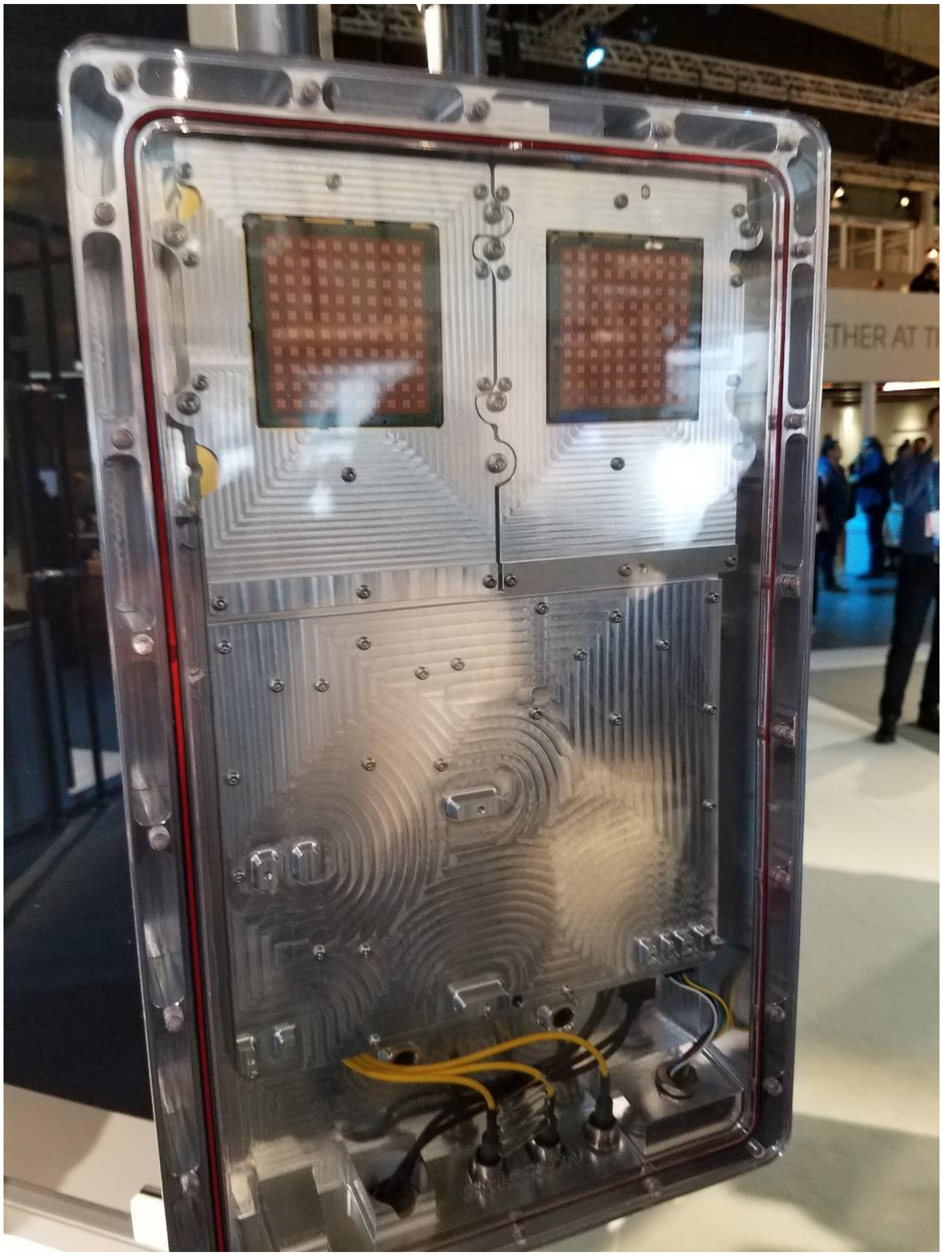

Figure 62. Ericsson high power mMIMO array, 28 GHz (2017 version, 2x 64T64R)

Source: Mobile Experts (MWC 2017 photo)

Figure 63. Ericsson 2017 mMIMO array, 28 GHz at +50 dBm EIRP (back side)

Source: Mobile Experts (MWC 2017 photo)

Figure 64. Ericsson 2018 mMIMO array, 192 elements at 28 GHz at +56 dBm EIRP

Source: Mobile Experts (MWC 2018 photo)

Figure 65. Ericsson mMIMO array, 192 elements at 28 GHz without baseband processing

Source: Mobile Experts (MWC 2018 photo)

Figure 66. Ericsson mMIMO array, 192 elements at 28 GHz with baseband processing

Source: Mobile Experts (MWC 2018 photo)

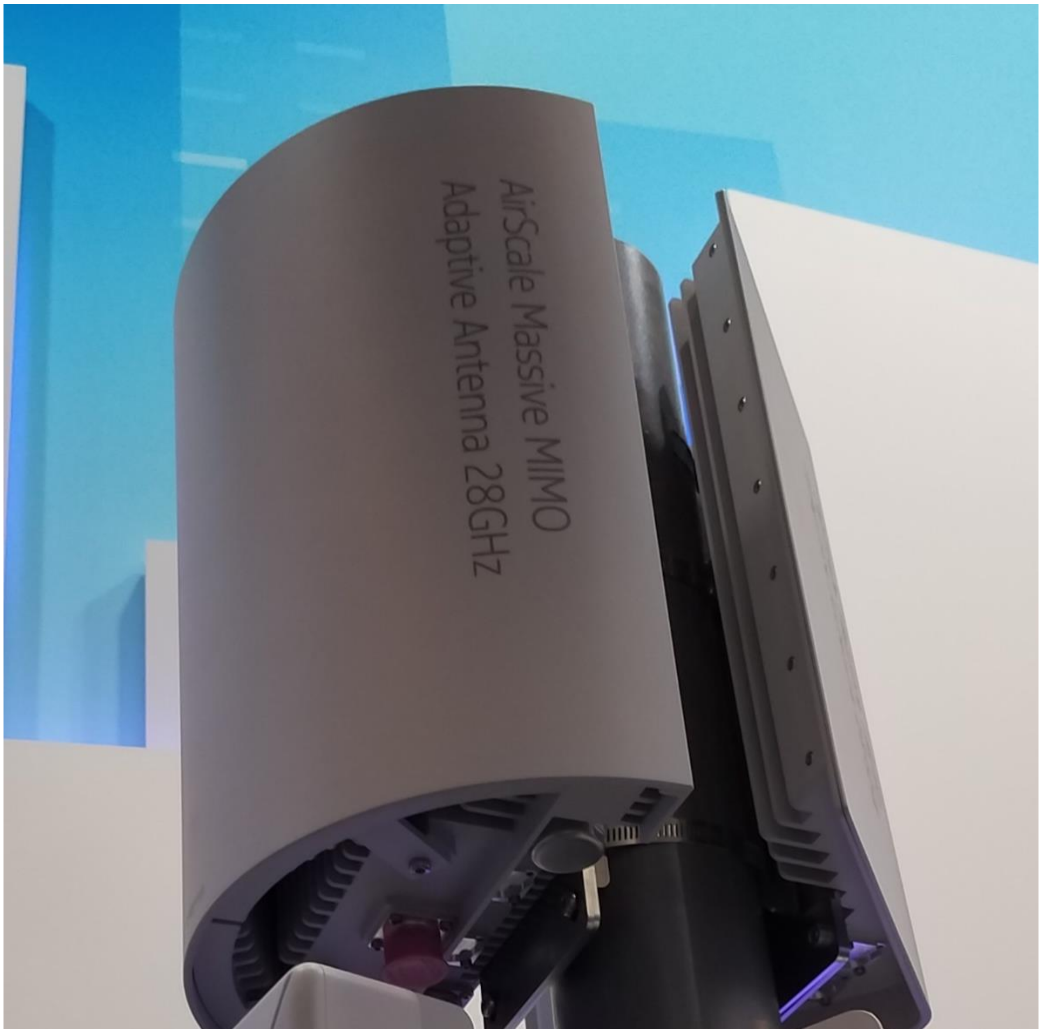

Figure 67. Nokia mMIMO array at 28 GHz, +51 dBm EIRP with 180 degree coverage

Source: Mobile Experts (MWC 2018 photo)

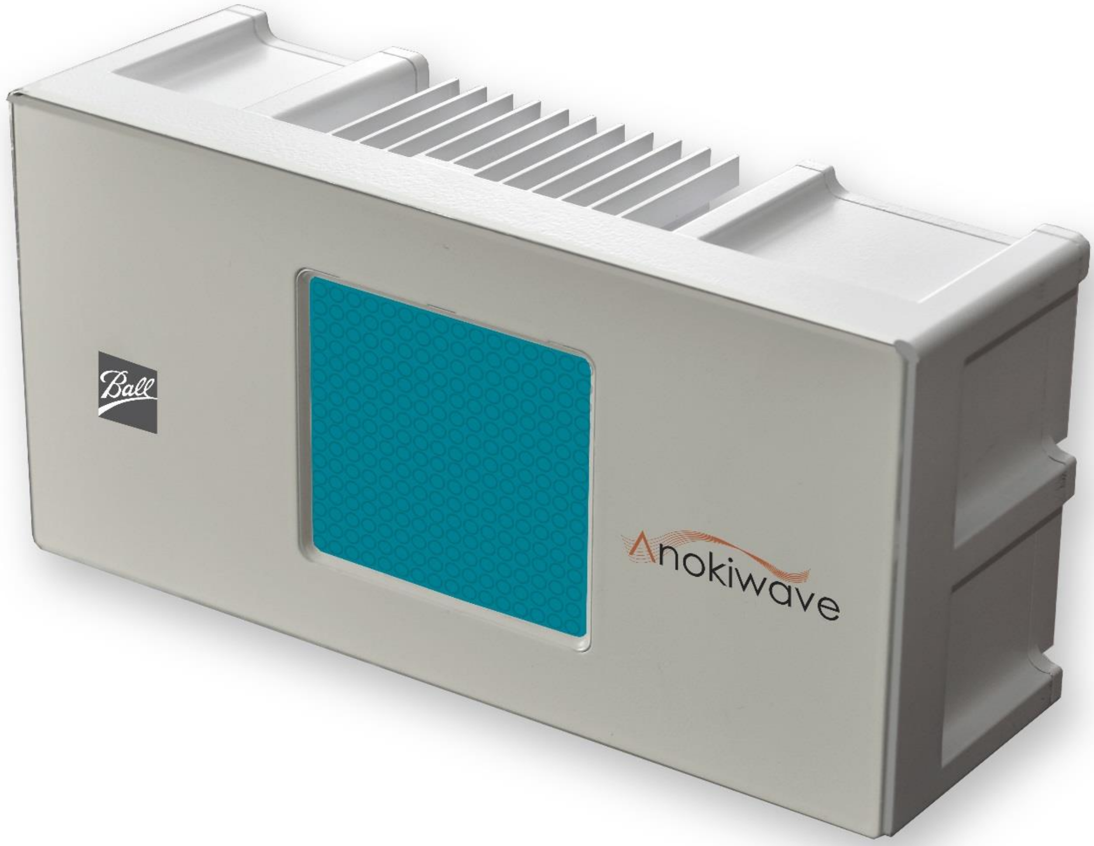

Figure 68. Anokiwave mMIMO array at 28 GHz, +60 dBm EIRP with 256 elements

Source: Anokiwave

Note the tiny heatsink for +60 dBm EIRP performance.

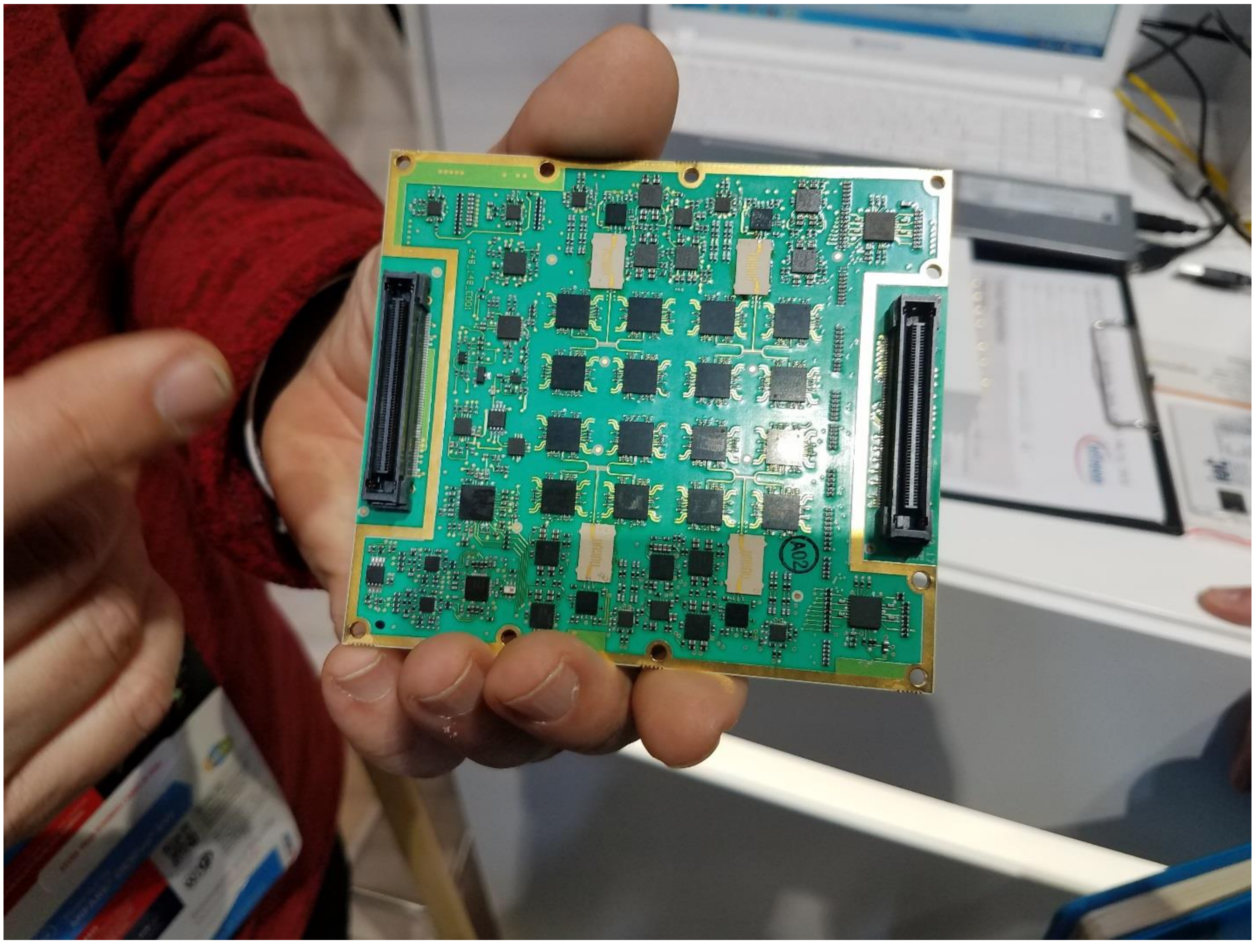

Figure 69. Infineon SiGe mMIMO array, 64 elements at 28 GHz with IF filtering

Source: Mobile Experts (MWC 2018 photo)

Active-Passive Integration of antennas

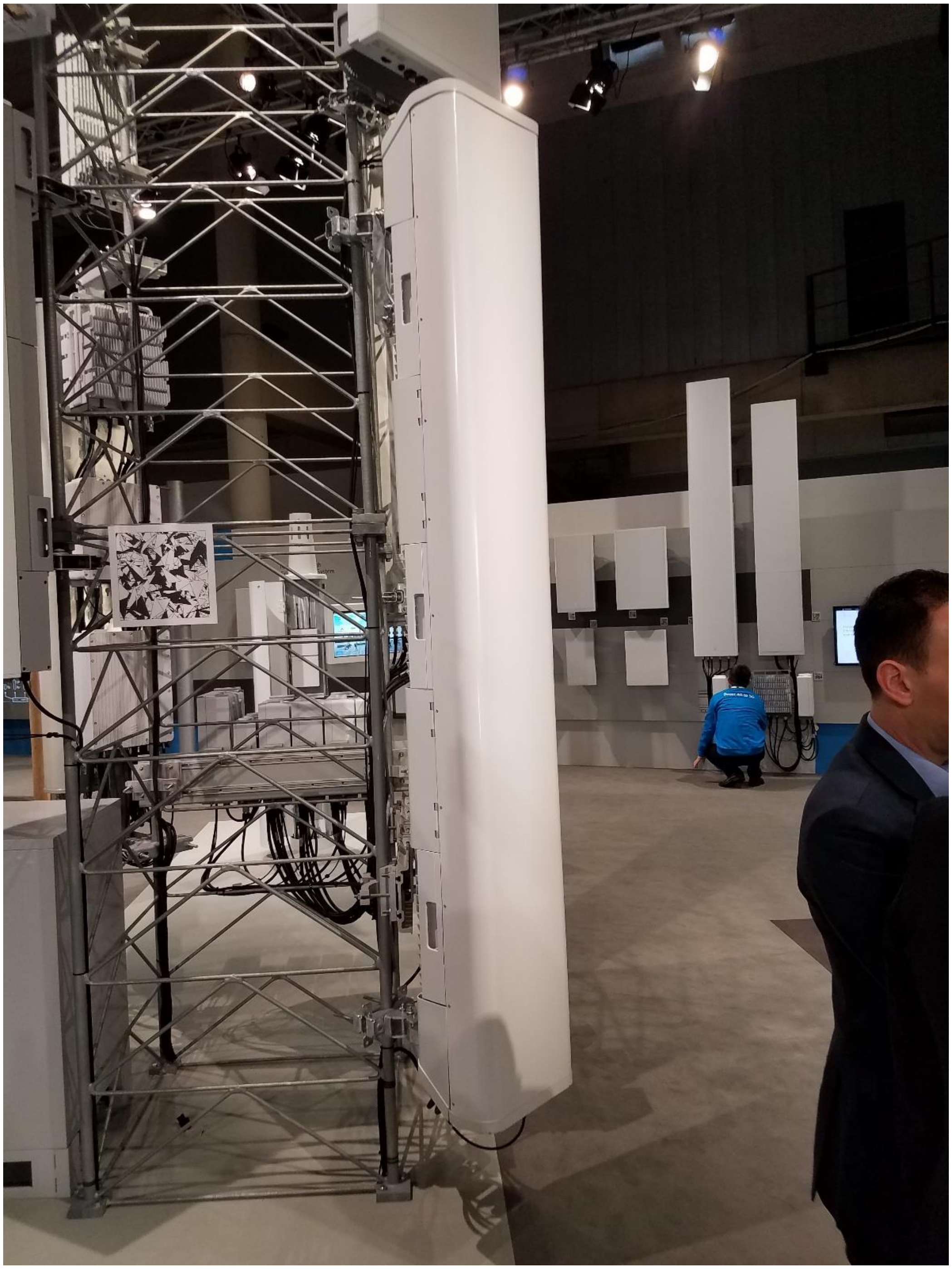

Figure 70. Ericsson 7-band active-passive antenna system (AIR 4488)

Source: Mobile Experts (MWC 2018 photo)

Figure 71. Ericsson 7-band active-passive antenna system, backside (AIR 4488)

Source: Mobile Experts (MWC 2018 photo)

Figure 72. Ericsson 7-band active-passive antenna system, bottom view (AIR 4488)

Source: Mobile Experts (MWC 2018 photo)

Figure 73.   Huawei active-passive antenna system, C-band array plus two FDD bands

Source: Mobile Experts (MWC 2018 photo)

Figure 74.   Huawei active-passive antenna system, bottom view of connectors

Source: Mobile Experts (MWC 2018 photo)

Client Devices above 20 GHz

Figure 75. Ericsson test CPE at 28 GHz ---still not size optimized as of March 2018

Source: Mobile Experts (MWC 2018 photo)

Figure 76. Samsung outdoor and indoor CPEs for fixed wireless at 28 GHz

Source: Samsung

Figure 77.   Fujitsu CPE at 28 GHz

Source: Mobile Experts (MWC 2018 photo)

Figure 78.   Samsung prototype tablet at 28 GHz (Used at US Super Bowl)

Source: Samsung

Note how Samsung exec is holding the tablet without covering antennas

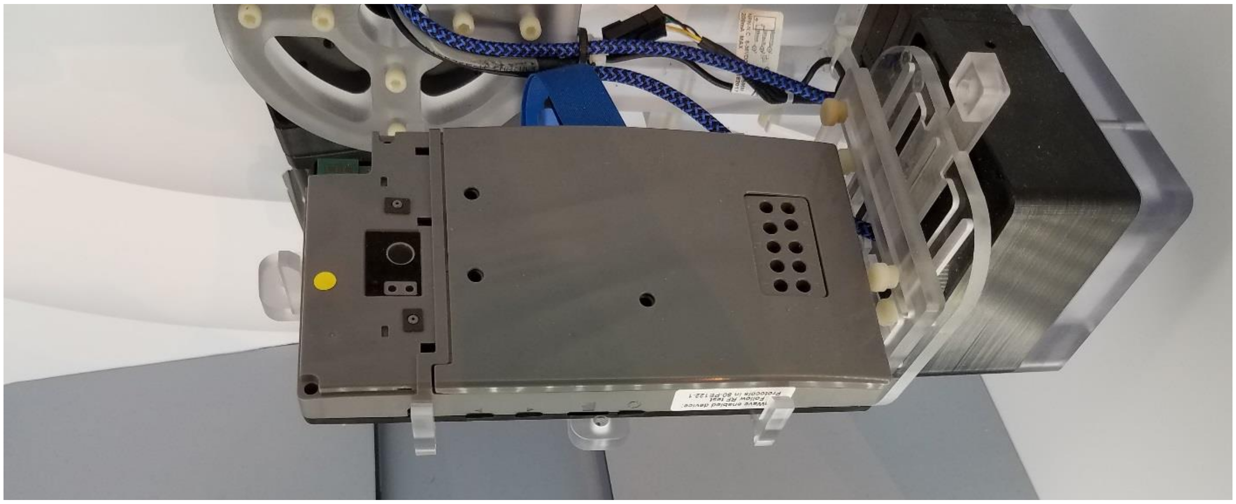

Figure 79. Qualcomm prototype handset at 28 GHz (two 4T4R subarrays)

Source: Mobile Experts (MWC 2018 photo)

Figure 80. Mediatek 28 GHz test handset (two 8T8R subarrays)

Source: Mobile Experts (MWC 2018 photo)